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Kinematics and stellar populations of the galactic bulge

Minniti, Dante, Ph.D.

The University of Arizona, 1993

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KINEMATICS AND STELLAR POPULATIONS
OF THE GALACTIC BULGE

by

Dante Minniti

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A Dissertation Submitted to the Faculty of the
DEPARTMENT OF ASTRONOMY
In Partial Fulfillment of the Requirements
For the Degree of
DOCTOR OF PHILOSOPHY
In the Graduate College
THE UNIVERSITY OF ARIZONA

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2

As members of the Final Examination Committee, we certify that we have
read the dissertation prepared by Dante Minniti

entitled Kinematics and Stellar Populations of
the Galactic Bulge

and recommend that it be accepted as fulfilling the dissertation
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Dedication

To Alicia

TABLE OF CONTENTS

LIST OF FIGURES	10
LIST OF TABLES	12
ABSTRACT	13
1. INTRODUCTION AND SUMMARY	14
1.1. History	14
1.2. Goals of This Dissertation	18
1.3. Definition of a Stellar Population	18
1.4. The Milky Way Galaxy	20
1.5. Scenarios of Galaxy Formation	21
1.5.1. The Dissipational Collapse Scenario	21
1.5.2. The Inhomogeneous Galaxy Formation	22
1.6. The Formation of the Bulge	23
1.7. The Role of the Clusters	24
1.8. The Size of the Bulge	25
1.9. Kinematics of the Bulge	26
1.10. Selection of the Fields	28
1.10.1. The Photometry	29
1.10.2. The Spectroscopy	30
1.11. Outline of this Dissertation	30
2. ABUNDANCES AND VELOCITIES FOR OPEN AND GLOBULAR CLUSTER GIANTS	32
2.1. Introduction	32
2.2. The Data	36
2.3. Spectroscopic Observations	40
2.3.1. Argus	40
2.3.2. MMT + Red Channel	41
2.3.3. Steward 90" + MX	42
2.3.4. Steward 90" + B&C	43
2.4. Reductions	43
2.4.1. Argus	44
2.4.2. MMT + Red Channel and 90" +B&C	45
2.4.3. Steward 90" + MX	46
2.5. Velocity Determinations	46
2.5.1. Argus Velocities	47
2.5.2. MMT and 90" Velocities	48
2.5.3. Cluster Membership	49
2.5.4. Velocity Errors	50
2.5.4.1. Argus: Repeated Measurements in 47Tuc	50
2.5.4.2. MX: Repeated Measurements in M3	52

TABLE OF CONTENTS – *Continued*

2.5.4.3. Red Channel: Repeated Measurements in M4	54
2.5.5. Comparison With Previous Cluster Velocities	54
2.6. The Abundance Determinations	58
2.7. The Calibration	81
2.7.1. $H\beta$	81
2.7.2. Fe Lines	81
2.7.3. Mg Features	83
2.7.4. Magnesium <i>vs</i> Iron	90
2.8. The Mg+2Fe Combined Index	94
2.8.1. Standard Clusters	94
2.8.2. Final Globular Cluster Abundances	99
2.8.3. Comparison with Previous Abundance Determinations	99
2.8.4. Comparison with Model Atmosphere Results	101
2.8.5. The Open Clusters	102
2.9. Conclusions	102
 3. IR PHOTOMETRY OF GLOBULAR CLUSTERS AND BULGE FIELDS	 105
3.1. Introduction	106
3.2. The Candidates	108
3.3. Observations	116
3.4. Reductions	117
3.5. Photometry	121
3.6. Calibration	126
3.7. The Color–Magnitude Diagrams	129
3.8. The Bulge Population	138
3.9. The Blanketing of Metal Rich Giants	147
3.10. The Spectroscopy	151
3.11. The Brightest Bulge Giants	160
3.12. Summary and Conclusions	162
 4. VELOCITIES AND ABUNDANCES FOR BULGE GIANTS IN FIELD F588	 165
4.1. Introduction	166
4.2. The Photometry	171
4.3. The Spectroscopy	179
4.4. The Reductions	181
4.5. The Velocities	182
4.6. The Abundance Determinations	183
4.7. The Data	187
4.8. The Metallicity Distribution	202
4.9. Kinematics <i>vs</i> Metallicity	206
4.10. The Halo Contamination	216

TABLE OF CONTENTS – *Continued*

4.11. The Thick Disk Contamination	217
4.12. The Disk Contamination	218
4.13. The 1st Moment of the Boltzmann Equation	223
4.14. The M Giants	227
4.15. Conclusions	228
 5. KINEMATICS OF BULGE GIANTS IN THE M22 FIELD	 231
5.1. Introduction	231
5.2. Selection of Candidates	232
5.2.1. The IR Photometry	233
5.3. The Spectroscopy	239
5.3.1. The Argus Observations	239
5.3.2. The MMT Red Channel Observations	241
5.3.3. Metallicities	243
5.4. Distances	243
5.5. Kinematics <i>vs</i> Metallicity	255
5.5.1. The M22 Members	255
5.5.2. The Bright Stars	257
5.5.3. The K Giants	257
5.5.4. The M Giants	261
5.6. Conclusions	261
 6. KINEMATICS OF A LOW LATITUDE FIELD	 263
6.1. Introduction	263
6.2. The Field F589	265
6.3. The Photometry	269
6.4. The Spectroscopy	273
6.4.1. The Observations	273
6.4.2. The Reductions	274
6.5. The Velocities	275
6.6. The Metal Abundances	277
6.7. What About Distances?	279
6.8. The Data	280
6.9. Contamination by other Populations	291
6.9.1. The Disk	291
6.9.2. The Thick Disk	303
6.10. Kinematics of Different Components	304
6.10.1. Halo Kinematics	304
6.10.2. Disk Kinematics	305
6.10.3. Bulge Kinematics	307
6.10.4. The M Giants	308
6.11. Conclusions	312

TABLE OF CONTENTS – *Continued*

7. KINEMATICS AND STELLAR POPULATIONS OF THE GALACTIC BULGE: IMPLICATIONS FOR GALAXY FORMATION ...	313
7.1. Introduction	313
7.2. Halo Kinematics as Function of Position	313
7.3. Bulge Kinematics as Function of Position	319
7.3.1. Bulge K Giants	319
7.3.2. Bulge M Giants	325
7.4. Other Tracers of the Bulge and Halo	327
7.4.1. The RR Lyraes	329
7.4.2. The Bulge Carbon Stars	330
7.4.3. The Planetary Nebulae	332
7.4.4. The OH/IR Stars	333
7.4.5. Miras and Other Long Period Variables	334
7.5. Chemical Evolution of the Bulge	335
7.6. The Metallicity Gradient	337
7.7. The Role of the Globular Clusters in the Inner Galaxy	343
7.7.1. Introduction	343
7.7.2. The Spatial Distribution	345
7.7.3. The Kinematics	348
7.7.4. The Ages	351
7.7.5. The Metal Abundances	353
7.7.6. The Formation History	356
7.7.7. Summary	357
7.8. The Formation of the Galactic Bulge	358
7.9. Conclusions	363
8. CONCLUSIONS	365
APPENDIX 1: A SIMPLE GALACTIC MODEL	370
A1.1. The Halo	371
A1.2. The Thin Disk	372
A1.3. The Thick Disk	373
A1.4. The Bulge	374
A1.5. Normalizations	375
A1.6. The Absorption	376
A1.7. Luminosity Functions	377
A1.8. Contributions Along the Line of Sight	379
A1.8.1. Discussion of Individual Fields	384
A1.9. IR Star counts in Bulge Fields	385
A1.10. Final Models	387
REFERENCES	393

LIST OF FIGURES

FIGURE 2.1. $H\beta$ index <i>vs</i> color	82
FIGURE 2.2. Fe5270 index <i>vs</i> color	84
FIGURE 2.3. Fe5335 index <i>vs</i> color	85
FIGURE 2.4. Fe5011 index <i>vs</i> color	86
FIGURE 2.5. Fe4920 index <i>vs</i> color	87
FIGURE 2.6. Fe4980 index <i>vs</i> color	88
FIGURE 2.7. Fe5400 index <i>vs</i> color	89
FIGURE 2.8. Mg index <i>vs</i> color	91
FIGURE 2.9. Mg indices for globular cluster giants	92
FIGURE 2.10. Mg indices for open cluster giants	93
FIGURE 2.11. Mg <i>vs</i> iron indices	95
FIGURE 2.12. Mg+2Fe index <i>vs</i> color	96
FIGURE 2.13. Indices for field stars	97
FIGURE 3.1. Map of the clusters observed	112
FIGURE 3.2. K mosaics of UKS1 and Pal6	118
FIGURE 3.3. IR color magnitude diagrams	130
FIGURE 3.4. Fiducial cluster lines	137
FIGURE 3.5. Spectral indices <i>vs</i> $(J-K)_0$	144
FIGURE 3.6. Mean abundances for bulge giants	155
FIGURE 4.1. APM photometry of F588	177
FIGURE 4.2. JHK photometry of F588	178
FIGURE 4.3. Photometry for the giants with spectra	203
FIGURE 4.4. Mg+2Fe <i>vs</i> color	204
FIGURE 4.5. Metallicity distribution	205
FIGURE 4.6. Heliocentric velocity <i>vs</i> Mg+2Fe	207
FIGURE 4.7. Dependence of velocity on spectral indices	208
FIGURE 4.8. Dependence of velocity on magnitude	209
FIGURE 4.9. Radial velocities <i>vs</i> final abundances	211
FIGURE 4.10. V_G and σ <i>vs</i> metallicity	212
FIGURE 4.11. V/σ <i>vs</i> metallicity	213
FIGURE 4.12. Velocity distributions	215
FIGURE 5.1. Optical color-magnitude diagram	234
FIGURE 5.2. IR color-magnitude diagram	240
FIGURE 5.3. Velocities <i>vs</i> magnitudes	242
FIGURE 5.4. Mg+2Fe index <i>vs</i> color	247
FIGURE 5.5. Metallicity distribution	248
FIGURE 5.6. Distribution of distances	251
FIGURE 5.7. Metal abundances <i>vs</i> distances	252
FIGURE 5.8. Velocity <i>vs</i> metallicity	258
FIGURE 5.9. Kinematics <i>vs</i> metallicity	260
FIGURE 6.1. Maps of the field F589	267
FIGURE 6.2. Color-magnitude and color-color diagrams	268
FIGURE 6.3. Photometry for the stars with spectra	271
FIGURE 6.4. Velocities <i>vs</i> magnitudes	272

LIST OF FIGURES – *Continued*

FIGURE 6.5. Mg index <i>vs</i> combined Fe index	293
FIGURE 6.6. Mg+2Fe index <i>vs</i> color	294
FIGURE 6.7. Metallicities <i>vs</i> color	295
FIGURE 6.8. Velocities <i>vs</i> metallicities	296
FIGURE 6.9. Kinematics <i>vs</i> Metallicity	310
FIGURE 6.10. Velocity distributions	311
FIGURE 7.1. Kinematics of halo giants	318
FIGURE 7.2. Kinematics of bulge giants	320
FIGURE 7.3. V/σ <i>vs</i> ϵ for halo and bulge	324
FIGURE 7.4. Mean metallicities in bulge fields	340
FIGURE 7.5. Metallicity <i>vs</i> Galactocentric distance	347
FIGURE 7.6. Concentration of metal rich clusters	352
FIGURE 7.7. Velocities for clusters with $R_G \leq 20^\circ$	355
FIGURE A.1. Absorption in K <i>vs</i> distance	378
FIGURE A.2. Distribution of giants for F588	380
FIGURE A.3. Distribution of giants for F589	381
FIGURE A.4. Distribution of giants for M22	382
FIGURE A.5. Distribution of giants for BW	383
FIGURE A.6. Distribution of giants for F588 (2nd normalization).....	389
FIGURE A.7. Distribution of giants for F589 (2nd normalization).....	390
FIGURE A.8. Distribution of giants for M22 (2nd normalization).....	391
FIGURE A.9. Distribution of giants for BW (2nd normalization).....	392

LIST OF TABLES

TABLE 2.1. Spectroscopic data collection	37
TABLE 2.2. Photometric data collection	37
TABLE 2.3. Clusters observed	39
TABLE 2.4. Velocities and Mg indices for 47 Tuc giants	51
TABLE 2.5. Individual velocities for M3 giants	53
TABLE 2.6. Radial velocities	55
TABLE 2.7. Definition of spectral indices	61
TABLE 2.8. Standard stars	63
TABLE 2.9. Spectral indices	65
TABLE 2.10. Photometry, velocities and abundances	73
TABLE 2.11. Derived cluster metallicities	100
TABLE 3.1. Observing runs	109
TABLE 3.2. Clusters observed	110
TABLE 3.3. Derived bulge parameters	114
TABLE 3.4. Spectroscopy	153
TABLE 3.5. Derived cluster parameters	158
TABLE 4.1. Spectroscopic indices	188
TABLE 4.2. Photometry, velocities, and abundances	193
TABLE 4.3. Kinematics <i>vs</i> Metallicity	200
TABLE 5.1. Photometry, velocities and abundances	235
TABLE 5.2. Spectroscopic indices	244
TABLE 5.3. Kinematics <i>vs</i> Metallicity	256
TABLE 6.1. Spectral indices	281
TABLE 6.2. Photometry, velocities and metallicities	286
TABLE 6.3. Kinematics <i>vs</i> metallicity	309
TABLE 7.1. Published velocities	328
TABLE 7.2. Metallicity determinations	338
TABLE A.1. Density law exponents for the bulge	388
TABLE A.2. IR star counts in bulge fields	388
TABLE A.3. Contributions from different components	388

ABSTRACT

In order to measure radial and/or rotation velocities and obtain metallicities for the stellar population of the Galactic bulge, several hundred spectra of giants have been obtained. These include three bulge fields at projected distances from the Galactic center of 1.5, 1.7 and 1.7 kpc, and 33 globular and open clusters. We measure metallicities based on a calibration from stars belonging to the field and to clusters of known abundances.

There is a clear dependence of the kinematics on metallicity in all the fields studied, in the sense that the more metal poor stars have lower rotation and higher velocity dispersion than the more metal rich stars. In particular, we identify the giants having $[\text{Fe}/\text{H}] \leq -1.0$ with an extension of the halo population to the innermost regions of the Galaxy rather than with the bulge itself.

Near-IR photometry of 21 globular clusters and bulge fields within 3 kpc of the Galactic center has also been obtained. We find a metallicity gradient with radial distance from the center, consistent with previous results obtained from optical photometry. We argue that the majority of the metal rich globulars within 3 kpc of the center are associated with the bulge population.

We also argue that the RR Lyraes previously studied in bulge fields are associated with the inner halo, and that the bulge is younger than the halo. Other kinematic tracers are examined (M giants, RR Lyraes, Miras, OH/IR stars, planetary nebulae) to associate them with different Galactic components. We conclude that all the existing evidence shows that dissipation played an important role in the formation of the bulge.

1. INTRODUCTION AND SUMMARY

This introductory chapter first gives a brief history of bulge research, to put into perspective how we arrive at the present knowledge of the bulge. Next, we summarize the goals of this dissertation, and the approach taken to achieve these goals. Then we give a brief introduction to the present knowledge on the subject, even though each chapter is formulated with its own introduction. Finally, the plan and outline of this dissertation is presented.

1.1. History

The Galactic bulge is clearly seen by the naked eye in the constellations of Scorpius–Sagittarius. Probably the Spanish and Portugese sailors that introduced the Magellanic clouds to the Occident also noticed the bulge clouds. Herschel (1847) delineated the Sagittarius cloud, but did not recognize it as the central part of the Galaxy (his maps are reproduced in Gilmore 1990). At the beginning of the century, the prevailing model of the Galaxy had the Sun close to its center (e.g. Kaptein & Van Rhijn 1920). Shapley (1918, 1919) recognized globular clusters as specific tracers of Galactic structure, and showed that they are concentrated in the direction of Sagittarius, changing the view of the Galaxy radically. This was confirmed by the discovery of Galactic rotation (Oort 1927, see also Lindblad 1927). The conception that our Galaxy is a spiral was reaffirmed by the realization of external galaxies (Hubble 1936). The general picture of the Galaxy has not changed much since the 1940's (e.g. Plaskett 1936).

Baade (1944a, 1944b) defined the concept of stellar populations, when he resolved the nearby galaxies M31, M32 and NGC205 into stars. It is important to remember that this is based on whether the brightest stars are blue or red, as in the color-magnitude diagrams (CMDs) of the Pleiades or M92. Baade (1951) also discovered RR Lyraes in a region of high density of stars towards the center of the Galaxy, that he chose because of the low obscuration. This window, now called Baade's window, allows us to look all the way through the Galaxy to the Galactic bulge, passing about 0.5 kpc from the center. In these dark optical ages, all that could be studied about the central component of the Galaxy was done through these windows. Baade's window has remained as the most important, most studied bulge field. Because of the RR Lyraes, Baade postulated that the bulge was old and metal poor, as the halo globular clusters. It seemed that the bulges of galaxies had the same CMDs as globular clusters.

Many different populations of stars were defined at the Vatican Conference in 1957 (O'Connell 1958), only 2 of these populations will survive. The classical concept of populations I and II, reviewed and summarized by Blaauw (1965), has been ever since well established as one of the major tools for Astrophysics.

The color-magnitude diagrams of clusters were the most useful tool to study stellar populations, open and globular clusters showed marked differences in the luminosity-temperature plane, and it was recognized early that the globular clusters were much older (e.g. Sandage and Schwarzschild 1952). Arp (1955, 1965) published photographic BV CMD of Baade's window, finding that the bulge population is globular cluster-like, showing few blue stars, a populated

red giant branch –RGB– and a red horizontal branch –HB– (see also van den Bergh 1971).

Going back to the end of last century, father Secchi contributed with his eye–spectral classifications (Maffeo 1991), discovering that some stars have strong bands (C and M stars). In the 1940's, the modern spectral classification scheme was developed (Morgan, Keenan & Kellman 1943). In the 1950's, Nassau, Blanco, and McCarthy looked for C and M stars all along the Galaxy and the Magellanic Clouds. Their major contribution was to establish that the ratio of C/M stars of the bulge was almost zero, in marked contrast with the Galactic disk (e.g. Nassau & Blanco 1958, Blanco 1965). This discovery challenged the hypothesis of Baade of an old, metal poor bulge.

Later, Whitford (1978) showed that the integrated spectra of bulge windows resembled those of distant elliptical galaxies and bulges. These galaxies have very strong lines, looking like a metal rich population, confirming the results of Morgan presented at the Vatican Conference (also Morgan & Mayall 1957). Much of the work on stellar populations concentrated on the stars we find in the Solar neighborhood, and until the last stages of the optical age, when solid state detectors became available, the bulge remained relatively ignored.

Then came the IR ages, when new light could shine through the dust of the Galactic disk thanks to single–channel bolometric detectors in the beginning, and to 2–dimensional arrays in the present. We are still in the IR age, and much work has to be done until we advance to the next era. The starting protagonists of bulge studies in the IR age are Whitford and Frogel (see Frogel

1988). They took advantage of the reduced extinction in the IR to study the bulge giants, despite the fact that the detectors were not very sensitive. One of the major contributions is the Frogel & Whitford (1987) paper, where they presented the bulge luminosity function, concluding that the bulge is indeed old. This was the first solid statement about the age of the bulge, based on the luminosity of the brightest giants. Rich and Terndrup, two of Whitford's students became the current protagonists of bulge research. Their theses followed up with the determination of the chemical abundance of bulge giants (Rich 1988), and with the determination of the age of the bulge via main sequence photometry (Terndrup 1988). As of the beginning of the 90's, the bulge has established itself as old and metal rich. Current research is focussed in attacking more subtle questions, like how rich is metal rich, and how old is old, and how did the bulge form.

In the 80's, the satellite observatories, starting with IRAS, provided us with a new view of the inner parts of the Galaxy (e.g. Habing 1985). Now we are all anxiously waiting for the results of COBE. Presently, there are major groups working in bulge research, and much progress is expected in this decade from the use of IR arrays. The next logical steps are to disentangle the relationship of the inner bulge and disk to the Galactic center, and to compare our bulge to other Local Group galaxies. After that, the only thing left will be to go there and check that we did everything right, but that will probably take a few more generations.

Spectroscopy also played its role in the 80's, with the first looks at the bulge kinematics by Mould (1983), followed by Freeman et al. (1988), which

proved that the velocity dispersion is $\sim 100 \text{ km s}^{-1}$. Since then, the studies of the kinematics and stellar populations have been concentrated to windows along the minor axis, which give no information about the rotation properties of the bulge. Early indications that the bulge is rotating were presented at the 1st ESO-CTIO meeting in 1989 (Catchpole 1990, Harding 1990, Menzies 1990), a conference that I could not attend. It was at that time when the work of this dissertation was formulated.

1.2. Goals of this Dissertation

The goals of this dissertation are:

- 1) To determine how the bulge fits into the stellar populations of the Galaxy.
- 2) To determine how the bulge was formed.

The selected approach to accomplish these goals is:

- 1) Get kinematics and abundances for bulge giants.
- 2) Study the clusters that might be associated with the bulge.

1.3. Definition of a Stellar Population

The characteristics defining each stellar population are: age, kinematics, spatial distribution and chemical composition. Traditionally, there were only two well defined populations. Pop I were all the young stars, located in the disks of galaxies, with high heavy metal abundance, and revolving at unison very rapidly around the centers of their galaxies, and Pop II, which are much older, distributed in spheroidal halos around galaxies, not rotating in unison

but with disorganized motions around the centers of galaxies, and with very low metal abundances.

This concept of stellar populations has evolved since Baade, as we have been able to study stars in more detail. Now we talk more about stellar populations associated with different galactic components. A typical galaxy like our own has a halo, a bulge, a thin disk and a thick disk (e.g. Gilmore & Reid 1983, van der Kruit & Searle 1981, Freeman 1987, Mould 1983). The last component may or may not be an extension of the thin disk (e.g. Gilmore & Wyse 1985, Norris, Bessell & Pickles 1985, Sandage & Fouts 1987, Carney, Latham & Laird 1989). Sometimes, these Galactic components overlap in metallicity, or kinematics, or age, or spatial distribution, but not all of these properties at the same time, which is what determines that they are separate components (e.g. Norris & Ryan 1991, Carney 1992). Unfortunately, most of what we know about the Galactic population components comes from observations near the Solar radius. The only exceptions are the clusters, which can be studied at large distances, and the bulge, which is not well represented in the Solar neighborhood.

The components of our Galaxy may have star clusters associated with them. Star clusters are very important, because we can determine their ages with relative ease, due to the fact that all the stars are coeval, lie at about the same distance and have similar chemical composition. By deciding which clusters, if any, are associated with the bulge, we can measure the ages of these clusters and have an idea if the bulge formed after or before the other components. We will argue that metal rich globular clusters are associated with the bulge, and

from their (very uncertain) ages we will conclude that the bulge formed after the halo, but before the thin disk.

1.4. The Milky Way Galaxy

We live in the disk of a spiral galaxy, called the Milky Way, at 8 kpc from its center, or about half way between the center and the "edge". In this Galactic disk relatively young stars are found, as well as interstellar clouds of gas and dust. The Galactic disk is the only place where new stars are being born nowadays. The thin disk is estimated to be 8–9 Gyr old at most (Janes 1988, Liebert et al. 1988, Demarque et al. 1992). The extended disk or thick disk could be older (e.g. Carney et al. 1990, Gilmore, Wyse & Kuijken 1991).

In contrast, the oldest stellar population is found in a spherically distributed halo. This halo was presumably the first formed component of the Galaxy, and its age has been measured to be about 15 Gyr, almost as old as the universe itself (e.g. Sandage 1986).

One of the goals of this dissertation is to determine how the Galactic bulge fits into the general scheme, i.e. to determine its relationship with the other Galactic components. It has been suggested in the literature that the bulge is a separate Galactic component, an extension of the thick disk, an extension of the thin disk, and the innermost part of the halo (e.g. Freeman 1987, Gilmore, Wyse & Kuijken 1991, Kormendy 1993, Terndrup 1993, Feast, Whitelock & Sharpless 1992, Carney 1993, etc). We will claim from the results of this dissertation that the bulge is a separate component, and not the extension of any of the others.

1.5. Scenarios of Galaxy Formation

The other goal of this dissertation is to try to determine how the bulge (and the galaxy) formed. Generally speaking, there are 2 competing scenarios for the formation of the Milky Way. These are championed by Eggen, Lynden Bell & Sandage (1962, hereafter ELS), and by Searle (1977), and Searle & Zinn (1978, hereafter SZ).

1.5.1. The Dissipational Collapse Scenario

In a blob of primordial gas (i.e. with zero metals) that is collapsing and forming stars, one expects to find a gradient in chemical composition, the most metal rich stars being more concentrated to the center. Likewise, as the gaseous cloud collapses forming stars, it collides with other clouds and loses energy by radiation, while angular momentum is conserved. Dissipation occurs in the gas, prior to star formation, and once stars are formed, the energy of the stellar system is conserved. The resulting system then will have a spheroidal distribution of older stars that are kinematically hot (i.e. have low rotation and high velocity dispersion), and younger stars that are more metal rich and kinematically colder. The distribution of younger stars then will be more concentrated towards the center and the plane with respect to the distribution of the older stars. Thus, a metallicity gradient will be observed. This is very briefly the dissipational collapse model of formation. In such a scenario, metallicity, age and kinematics are correlated. This scenario was championed by ELS, who seek to explain the formation of the halo and disk. This model was explored

theoretically by Larson (1976). We will argue later in the dissertation that this is probably how the bulge was formed. If the collapse takes place conserving energy (dissipationless collapse), no metallicity gradient will be observed.

1.5.2. The Inhomogeneous Galaxy Formation

Searle (1977) and SZ proposed that the halo formed from the coalescence of smaller protogalactic fragments, during an extended period of time, in a collapse that was not homogeneous. This is reminiscent of the merger scenarios advanced by Toomre (1977). The formation process for the halo lasted $\sim 1/4$ of the age of the universe, as judged from the ages of the oldest, more metal poor globular clusters (e.g. VandenBerg, Bolte & Stetson 1990, Green & Norris 1990, Carney et al. 1992). In this SZ scenario, it is not obvious that there will be a metallicity gradient. Nowadays, this is the preferred description for halo formation, and we will argue later that this is not in contradiction with the bulge having formed in an ELS-type collapse.

Yet the process of formation of our Galaxy (or any other spiral for that matter) is not known. In particular, the central component of the Milky Way, the Galactic bulge, is very important to disentangle the formation history. Intuitively, one would expect that in a system forming from the gaseous relics of the Big Bang, which has just stopped expanding under its own gravitational pull, all the action will occur in the center of the system. The action in this case is the formation of stars.

1.6. Formation of the Bulge

The formation of the bulge has not received as much attention as the formation of the halo, perhaps under the assumption that they were parts of a single component (the "spheroid"). However, the evidence for bulge formation is contradictory. The Galactic bulge is said both to be older than the halo (e.g. Lee 1992, Renzini 1992), or as young as the disk (e.g. Harmon & Gilmore 1988, Rich 1991). There are many difficulties in studying the bulge stars. These difficulties are associated with the location of the bulge, at low Galactic latitudes. To study the bulge stars we have to look all the way through the plane of the Milky Way, where the obscuration is very large and variable ($A_V \sim 30$ magnitudes for the Galactic center!). Furthermore, towards the center of the Galaxy the stellar density of the other Galactic components (disk and halo) must also reach a maximum, these fields are very crowded. However, is it fair to extrapolate the halo into the inner regions? We do not know how the halo or disk extend into a few kiloparsecs from the Galactic center.

This dissertation presents a large dataset, consisting of optical and IR photometry and spectroscopy of bulge giants. Velocities and abundances derived from these data are used to study the signatures of the formation of our Galaxy: the chemical abundances, kinematics and ages of the bulge stellar population. The optical and near-IR photometry are used to select bulge giants. The spectroscopy of these stars gives the radial velocities and metal abundances.

These data permit a clear separation between the bulge and halo. These Galactic components differ both in kinematics and chemical composition, and

we will speculate that they also differ in age.

Our results indicate that the inner portions of the Galaxy, the Galactic bulge, may have formed by a dissipational collapse. We find a clear correlation between metal abundance and kinematics of stars in the Galactic bulge. The oldest stars in the Galaxy are then found in these inner regions, and they belong to the Galactic halo. The galactic bulge is old, but it formed after the halo.

1.7. The Role of the Clusters

Another difficulty for studies of the bulge is that in the Solar neighborhood one finds two kinds of stars: metal rich, young and old disk stars, and metal poor, old halo stars. The bulge, however, is metal rich and old (e.g. Terndrup 1988, Rich 1988). There are not many calibrators nearby that we can use as standards for the determination of abundances in the bulge giants. We have then decided to use the metal rich globular clusters.

The association of the metal poor globular clusters with the halo has resulted in an enormous progress in the study of the halo, even though they are only 1 % of the mass of the halo (e.g. Kinman 1959). These clusters are visible at large distances, and their study can give relatively accurate measurements of ages and chemical composition. The distances are, in principle, also easy to determine.

There is a subset of these globulars that are more metal rich, and are more concentrated towards the Galactic disk and towards the Galactic center. They are still old, but perhaps 2–4 Gyrs younger than the typical halo clusters (Zinn 1993, Sarajedini & King 1993, Vandenberg & Stetson 1990). These clusters were

associated with the thick disk, which is an older portion of the disk (e.g. Zinn 1985, Armandroff 1988, Armandroff 1993). The thick disk is perhaps a separate component of the Galactic disk, that had a different formation history (e.g. Gilmore & Wyse 1985, Carney, Laird & Latham 1990, Norris 1986).

We have observed a large sample of globular clusters within 3 kpc of the Galactic center. These are in general the less well studied clusters, due to the heavy extinction and field contamination. Even though most of them have known radial velocities, their reddenings, abundances and distances are very uncertain. From IR photometry, we hope to add useful data to constrain these parameters, and study the connection with the Galactic bulge.

Armed with the bulge kinematics and abundances, we will compare the bulge with the metal rich globulars. The present results suggest that most of the metal rich globulars could be associated with the bulge rather than the disk of the Galaxy. This is concluded after the kinematic and metallicity data are analyzed. The bulge rotates as do the metal rich globulars, perhaps not as fast as the disk. The overlap in abundances between the metal rich globulars and the bulge is significantly larger than the overlap with the thick disk abundances.

This would also point to the metal rich bulge forming after the halo, (although a small overlap in ages cannot be discarded) lending support to the dissipational collapse scenario of formation for the inner Galaxy.

1.8. The Size of the Bulge

We will briefly discuss what we understand for bulge of the Galaxy, just in terms of its spatial extent, before we study the kinematics and stellar

populations. This is necessary to check that the fields studied do indeed include bulge stars. Rich (1991, 1993) argues that the bulge is confined to the inner kiloparsec. However, metal rich stars with bulge kinematics are found even in our fields at 1.7 kpc from the center. This was expected, since the metal rich stars have a velocity dispersion of the order of 100 km/s at Baade's window (Rich 1990).

The size of the IRAS bulge is $|b| \leq 10^\circ$, and $|l| \leq 15^\circ$ (e.g. Harmon & Gilmore 1988, van der Veen & Habing 1990). This size is determined from tracers associated with a metal rich population, which is known to be more concentrated (e.g. Frogel 1988). The size of the bulge as seen by COBE is similar: according to Weiland et al. (1993), the bulge is clearly seen in the 1.24 to 4.9 μm DIRBE maps to be confined within $\sim 10^\circ$ in latitude, and within $\sim 15^\circ$ in longitude. The real bulge will extend further than the surface brightness limit of these maps, and we will assume that the bulk of the bulge population is confined to the inner $\sim 20^\circ$. The lowest surface density contours of 2.4 μm emission also extends that far (Kent et al. 1991). This is not to say that the metal rich population is not more concentrated. Gilmore (1990) talks about an inner bulge ($R \leq 1$ kpc), and a main bulge ($1 \leq R \leq 3$ kpc). Note that it is not clear if the bulge is represented in the Solar neighborhood (e.g. Grenon 1989, Hernandez-Pajares 1993).

1.9. Kinematics of the Bulge

Kormendy & Illingworth (1982) and later studies (see Binney & Tremaine 1987 and references therein) have established that while the flattening of bright

elliptical galaxies is due to velocity anisotropies, the bulges of most spiral galaxies rotate fast enough to explain all the observed flattening. Typically, bulges of spiral galaxies like the Milky Way have $V_{rot} \sim 100 \text{ km s}^{-1}$, and $\sigma = 100 \text{ km s}^{-1}$. However, in our own Galaxy the rotation properties of the bulge are very poorly known.

The only field in the Galactic bulge for which the kinematics have been extensively studied is Baade's window at $l, b = (0.9, -3.9)$. The evolved stellar population there shows a mean metal abundance above solar (Rich 1988), and a large velocity dispersion (Mould 1983, Rich 1990). The behavior of the velocity dispersion and rotation as functions of position or chemical composition have yet to be mapped throughout the bulge. Such information is needed to answer questions about the history and formation of the bulge, and its place in our general picture of the Galaxy. In particular, should the bulge be considered part of the spheroidal halo, of the thick disk, or as a separate component? If the bulge formed by a coherent rapid collapse, its metallicity, central concentration, and degree of rotational support may be positively correlated. If, on the other hand, the collapse was more inhomogeneous, for example, the bulge formed by mergers or through accretion of an independent metal-rich object, such correlations may not exist.

With the ultimate goal of determining how the bulge formed, we have decided to study the kinematics and stellar populations of three off-axis fields at $l, b = (8, 7)$, $(8, 10)$ and $(12, 3)$. We find the rotation velocities and dispersions as a function of metallicity based on spectra of large numbers of K giants in these

fields. Minniti et al. (1992) published a preliminary study of the kinematics in the fields F588 and F589. However, their sample was small enough to prevent a division according to metal abundance, a much larger sample was needed. This dissertation presents a data set 5 times larger, from which we can study the relationships between V_{rot} , σ , and $[Fe/H]$ for the bulge in detail.

1.10. Selection of the Fields

Baade's window is the classic field where we learned most of what we knew about the bulge until the last decade. Other fields along the Galactic minor axis are now relatively well studied (e.g. Terndrup 1988, Frogel et al. 1991). These minor axis fields are very useful because they give an idea of the structure of the bulge, and how its stellar population changes with distance from the Galactic center. However, they do not provide much kinematic information other than the velocity dispersion. Off axis fields are needed to study the rotation of the bulge.

We have selected 3 off axis fields contained within the IRAS and COBE bulge, observable from the Northern hemisphere, and spanning a range of Galactic latitudes and longitudes. They were chosen to be "windows" of low obscuration, through which a clearer view of the bulge can be obtained. Some windows are located at a very low Galactic latitude, where the contribution of stars from the disk itself is very significant. The other windows are located further away from the plane, where only bulge and halo giants are found.

We have identified two relatively clear windows towards the Galactic bulge from visual inspection of the POSS (O and E plates), the ESO and SRC Southern

sky surveys (B_J , R, I and N plates), the Kyoto $H\alpha$ survey, and the IRAS (12, 25, 60 and 100 μm) surveys. The windows, named after their ESO plate number, are Field 588 at $l, b = (8, 7)$ or $\alpha, \delta = (17:40, -18:10)$, a projected distance from the Galactic center of 1.5 kpc, and Field 589 at $l, b = (12, 3)$ or $\alpha, \delta = (18:00, -17:45)$, a projected distance of 1.7 kpc (for $R_0 = 8$ kpc). The third field is that of the globular cluster M22, located at $l, b = (9.9, -7.6)$, at a projected distance of 1.7 kpc from the Galactic center. This field was selected because Cudworth (1986) measured proper motions for several suspected bulge giants. This field is not a window *per se*, but its reddening is relatively low ($E(B-V) = 0.32$). Even though the M22 field is complicated by the presence of cluster members, based on the proper motions one can select reliable bulge candidates.

Field F588 appears as a uniform region with a radius of about one degree, with a high density of stars, and with no obvious dust lanes. The central ~ 30 arcminutes of field F589 also appears uniform in terms of extinction. However, the outer parts show dramatic changes in reddening. These obscured regions will be included in our study, because they help to account for the disk contribution. The field of the globular cluster M22 also appears to be relatively uniform in terms of extinction. As discussed by Minniti et al. (1991), the SE part of the M22 field is only slightly more reddened.

1.10.1. The Photometry

In this dissertation we present near-IR photometry of over 1500 frames of globular clusters and bulge fields. The total number of stars for which JK

photometry is obtained exceeds 35,000. Here we present a preliminary analysis of the photometry, which clearly warrants further investigation.

1.10.2. The Spectroscopy

We also present 2–4 Å resolution spectra of the Mg5170 Å region for ~ 1000 giants towards different bulge fields, along with ~ 400 more spectra of standards. The size of this sample is only matched by the survey of Terndrup (in preparation), who is studying M giants in different bulge fields. Both studies are complementary.

1.11. Outline of this Dissertation

Chapter 2 gives a description of the spectroscopic data, their reductions and calibrations. A large data set for giants in open and globular clusters is presented, along with the calibration of spectral indices to give metallicities, and a description of radial velocity determinations.

Chapter 3 presents the IR photometry of globular clusters and bulge fields, along with spectroscopic determinations of metal abundances for some bulge globulars. We compare the giant branches of metal rich globulars with the bulge population, and determine the presence of a metallicity gradient in the bulge.

Chapter 4 is the study of field F588, where we present metallicities and velocities for bulge and halo giants. Here we will argue that: 1) Halo and bulge are 2 distinct components, 2) there is a trend of kinematics with metallicity, suggesting a bulge formation via dissipational collapse.

In chapter 5 we present velocities and abundances for bulge giants in the M22 field, discussing the trends of kinematics with metallicity.

Chapter 6 is the study of the low latitude field F589, with highly variable reddening. We identify the different components (halo, disk and bulge), and make an attempt at separating their kinematics.

Chapter 7 gives a comparative study of the different fields. We examine different populations present in the bulge, in an attempt to decide how the bulge formed. A discussion of our preferred scenario for bulge formation is given based on all the evidence (kinematics vs metallicity, age, globulars). It is argued that the bulge formed by a dissipational collapse, after the halo, and before the disk. The globular clusters in relation with the bulge are also discussed in chapter 7. Here we claim that not all the metal rich globulars are associated with the thick disk, but that the majority of them belong to the bulge.

Chapter 8 gives a very condensed summary of the major conclusions of this dissertation, and briefly discusses possible avenues of further research on the subject.

2. ABUNDANCES AND VELOCITIES FOR OPEN AND GLOBULAR CLUSTER GIANTS

In this section we describe the reductions of the optical and near-IR photometry, and the reductions of the spectroscopic data. We also describe the steps followed to determine radial velocities. Finally, we define spectroscopic indices and construct a grid for the determination of metallicities of K giants. The errors involved in the determination of radial velocities and $[\text{Fe}/\text{H}]$ are carefully examined.

We have analyzed a large number of giants in the field, and in open and globular clusters, to define a grid in the T_{eff} , L and g space that will allow the determination of metal abundances for bulge giants. A total of 110 giants were observed in the fields of 8 open clusters. A total of 340 giants were observed in the fields of 25 globular clusters. A total of 36 field stars with well known abundances and luminosities were also observed.

Adopting as standards the globular clusters NGC6356, 47 Tuc, M4, M3, and M22 we derive metallicities for a large sample of globular clusters with less well known compositions. These include the poorly studied globular clusters NGC6401, NGC6325, HP1, Pal6, NGC6517, NGC6642, and NGC6366.

2.1. Introduction

The absolute metallicity of the bulge is an important datum needed to decipher its history of formation, and that of the Galaxy in general. Different

scenarios predict different absolute iron abundances and element abundance ratios (Matteucci & Brocato 1990).

To study the dependence of kinematics on metallicity in the bulge, one needs to measure metal abundances for old, metal rich stars. It then seems reasonable to use the metal rich globulars as calibrators. However, just how metal rich do the metal rich globulars get? Are there any globulars that are metal rich enough to serve as calibrators for the bulge giants? The compilations of Webbink (1985), Armandroff & Zinn (1988), and Armandroff (1989) list a few clusters with $[\text{Fe}/\text{H}] \geq 0$. Given that the mean metallicity of bulge giants was revised to be more metal poor by ~ 0.35 dex by McWilliam & Rich (1993), there exists the possibility of still using globulars as calibrators for the study of the bulge. In particular, the color-magnitude diagram (CMD) of Ter1 reveals that this cluster is more metal rich than the bulge population at Baade's window (Ortolani et al. 1993). Ortolani et al. (1993) obtain $[\text{M}/\text{H}] \geq 0.5$ for Ter1 both from spectroscopy and photometry. This means that it is possible to use the globulars as calibrators without the need of extrapolating the scale to measure metal abundances, provided one can find the right indices.

What method should one use for the metallicity determination of bulge giants? Ideally, one would like to obtain high dispersion, high S/N spectra and do a model atmosphere analysis as McWilliam & Rich (1993). This is impossible, however, for more than a few stars. There are more expedient methods: pseudo-equivalent widths of the Ca II triplet, the MgI triplet, or iron lines, or colors of giants (V-K, J-K, BVI). However, it is difficult to choose which one is the best.

The BVI CMDs allow the ranking of globular clusters according to $[\text{Fe}/\text{H}]$ (DaCosta & Armandroff 1990). This was extended to more metal rich globulars by Ortolani et al. (1991), who find that the red giant branch (RGB) bends over for the reddest stars. The method used by Ortolani et al. (1990, 1992), require precise observations of large regions with uniform extinction, due to the paucity of the reddest RGB stars, and has to be properly calibrated itself.

The Ca II triplet applied to individual giants in LMC clusters and to globular cluster calibrators is discussed by Olszewski et al. (1991). Giants in Galactic globulars have been also observed by Armandroff & DaCosta (1991). They find that the calibration brakes down for the metal rich globulars. They caution against the use of this method for $[\text{Fe}/\text{H}] \leq -1.2$, due to the loss of sensitivity and possible changes in the $[\text{Ca}/\text{Fe}]$ abundances. The study of open clusters with this system will be profitable, because the $[\text{Ca}/\text{Fe}]$ ratio might be different and therefore both populations could define different calibrations. Further observations by Suntzeff et al. (1993) demonstrate the usefulness of the Ca II triplet for abundances close to solar, because they include the globular cluster NGC5927 at $[\text{Fe}/\text{H}] = -0.3$ (note that they put M67 on the same footing, even though there is no reason to assume that the open clusters follow the same calibration, i.e. is $[\text{Ca}/\text{Fe}] \propto [\text{Fe}/\text{H}]?$).

The techniques outlined above have some contradictory results, which made the selection of a method harder.

Armandroff & Zinn (1998) obtain for Ter1 the same metallicity as 47Tuc ($[\text{Fe}/\text{H}] = -0.7$), based on integrated spectra at the Ca II triplet. However,

Ortolani et al. (1990) rank Ter1 as the most metal rich cluster of their sample, more metal rich than NGC6528, NGC6553 and NGC6356, and more metal rich than the bulge giants at Baade's window, based on the RGB morphology in the BVI CMDs.

Frogel, Persson & Cohen (1983) found from integrated photometry $(J-K)_0 = 0.93$ for the cluster NGC6553, much bluer than the relation they define for the globular clusters. However, Aaronson & Malkan (unpublished), find the integrated color of NGC6553 to be $J-K_0 = 0.97$. The integrated light for such a cluster is dominated by stars on the RGB and AGB of their evolution (Buzzoni 1990). In consequence, the integrated color of a cluster cannot be redder than the RGB locus.

Francois (1990) obtained $[Fe/H] = -0.7$ for NGC5927, based on high dispersion spectra of one giant and model atmosphere analysis. On the other hand, McWilliam & Rich (1993) obtain for this cluster $[Fe/H] = -0.3$, from high dispersion spectroscopy and model atmosphere analysis of another single giant. NGC5927 is a bright cluster, traditionally used for the calibration of the metal rich end of the scale in studies of bulge fields (e.g. Rich 1988).

For the bulge giants, the use of the spectroscopic line indices like the MgI triplet at $\lambda 5175 \text{ \AA}$, combined with the Fe lines at $\lambda 5270 \text{ \AA}$ and $\lambda 5335 \text{ \AA}$ gives controversial results (Rich 1988 *vs* McWilliam & Rich 1993). Hereafter, we will refer to this combination of indices as $Mg+2Fe$.

Integrated spectra usually more practical to use for concentrated clusters in uncrowded fields (e.g. Armandroff & Zinn 1989). Individual stars are the only

hope to measure the metallicities of sparse clusters in more crowded fields, with the trade-off that membership should be established.

For a number of reasons we decided to use the Mg 5175 region of the spectrum. One is that the indices found in this region are of wide use in a wide variety of contexts, including the study of ellipticals and bulges of spiral galaxies. The calibration for the very metal rich end has been a long standing problem. Also, the Ca II triplet at λ 8550 Å was believed not to be useful for metal rich stars at the time we started this project. We have then decided to recalibrate the Mg+2Fe indices, using a large sample of giants in globular clusters, with the care of including as many metal rich clusters as possible. It is important to observe a number of giants per cluster, to define clearly the mean cluster abundance, due to the large scatter shown by the metal rich globulars.

Here we discuss the determination of metallicities and velocities for open and globular cluster giants. The aim is to set up an abundance calibration to use for the study of bulge giants, and at the same time check the errors in the metallicities and velocities derived by our techniques. In this chapter we pay particular attention to the description of the observations and reductions of the spectroscopic data that we will use throughout this thesis.

2.2. The Data

In tables 1 and 2 we summarize the spectroscopic and photometric runs that are the basis for this thesis (even though not all of them are relevant for this particular chapter). The location of the fields listed was defined in chapter 1.

Table 2.1: Spectroscopic Data Collection

Date	Telescope	Instrument	Field	N*s
Jun 89	90"	B&C+Reticon	F588,F589	12
Jul 89	90"	MX	F588,F589	50
Jun 89	MMT	Red Channel	F588,F589	60
Jul 90	90"	MX	F588,F589	100
Jun 91	MMT	Red Channel	M22,M28	50
Jul 92	CTIO 4m	Argus	F588,M22, std cl.	320,44, 280
Jul 92	100"OCIW	Multifiber	F589	250
May 92	90"	B&C	cl giants	25
Jun 92	90"	B&C	cl giants	25
Jun 92	MMT	Red Channel	cl giants M22,M28	50, 40,33

Table 2.2: Photometric Data Collection

Photometric Data Collection				
Date	Tel.	Instrument	Type	Field
	UKS	plates/APM	BRI	F588,1Dx1D F589,2Dx2D
Jun89	90"	TI 800x800	BRI	F588,F589,2x2'
Jun90	61"	Nicmos2	JHK	F588,20x20' F589,20x20'
Jul92	90"	Loral 2kx2k	BRI	F588,F589,5x5' M92
Jun91	90"	Nicmos3	JK	bulge globs
May92	90"	Nicmos3	K	bulge globs
			K	SgrI,M28
Jun92	90"	Nicmos3	Ks	F588 deep
			J	bulge globs

Table 3 lists the open and globular clusters observed. Columns 2 and 3 are the metal abundance and the reddening, respectively, from the compilation of Armandroff (1989), or of Webbink (1985) otherwise. Column 4 lists the cluster age when known. Column 5 is the number of stars for which good quality spectra have been obtained (not all of these are cluster members, as discussed below). Column 6 gives the references for the metallicities, and column 7 gives the sources of the stellar photometry. Finally, column 8 lists the clusters for which we have obtained JK photometry.

A sample of giants in each cluster was chosen from published CMDs, preferably of high quality. Stars in the RGB were selected, trying to avoid AGB stars (although this was impossible in most cases). Typically, the giants are found between the RGB tip and 2.5 magnitudes fainter. Known variables were avoided. This was relatively simple in the standard, well studied clusters. However, the clusters projected on the bulge do not have good CMDs in general, that would allow the discrimination between field and cluster giants. In these clusters, the radial velocity measurements provide an invaluable membership criterion.

For the rest of the clusters with no photometry published, which lie in the Galactic bulge, it is very important to choose the candidates carefully, to avoid being overwhelmed by bulge giants. In consequence, we have taken IR photometry of most of these clusters to select the candidates. Even though the IR photometry allows us to select giants well into the cluster cores to increase cluster membership, the photometric errors increase in these crowded regions,

Table 2.3: CLUSTERS OBSERVED

Cluster	[Fe/H]	Age	E_{B-V}	N	Phot	Reference
NGC2141	-0.60	4.0	0.35	15	BV	FJ93
NGC2158	-0.58	3.0	0.40	20	BV	FJ93
NGC2204	-0.58	3.0	0.08	14	BV	FJ93
NGC2243	-0.56	5.0	0.05	12	BV	FJ93
NGC2477	-0.05	1.3	0.30	17	BV	FJ93
NGC2506	-0.52	4.0	0.05	20	BV	FJ93
NGC6819	0.05	2.3	0.27	7	BV	FJ93
NGC6791	0.23	7.5	0.12	4	BV	FJ93
47Tuc	-0.71	13.0	0.04	47	BV	A89
NGC288	-1.40	16.0	0.04	15	BV	A89
NGC362	-1.28	13.0	0.07	14	BV	A89
NGC1851	-1.29	....	0.02	15	BV	A89
M4	-1.05	16.0	0.40	24	IR	A89-DSS92
M3	-1.66	13.0	0.00	20	BV	A89
NGC6624	-0.37	....	0.25	29	BV	A89
NGC6637	-0.59	....	0.17	14	BV	A89
M22	-1.75	....	0.32	10	IR	A89
M28	-1.30	....	0.40	6	IR	A89
NGC6356	-0.54	....	0.50	14	IR	A89
NGC6553	-0.29	....	0.82	6	BV	A89
M15	-2.25	16.0	0.10	4	BV	A89
M71	-0.58	13.0	0.27	3	BV	A89
NGC6401	-1.01	....	0.79	13	IR	A89
NGC6402	-1.39	....	0.59	2	BV	A89
NGC6366	-0.99	....	0.70	3	BV	A89
NGC5466	-2.22	....	0.00	1	BV	A89
HP1	-0.50	....	1.41	5	IR	A89
NGC6528	-0.23	....	0.56	7	IR	A89
Pal6	0.22	....	1.45	5	IR	A89
NGC6440	-0.34	....	1.10	5	IR	A89
NGC6325	-1.44	....	0.89	4	IR	A89
NGC6517	-1.34	....	1.08	6	IR	A89
NGC6642	-1.30	....	0.36	5	IR	A89

Notes to Table 1:

A89 = Armandroff (1989), FJ92 = Friel & Janes (1993),
W85 = Webbink (1985), DSS92 = Drake, Smith & Suntzeff
(1992), SOMW92 = Suntzeff et al. (1992)

and variables are not discriminated. The sources for the star identifications are listed in the notes to table 3, except for the clusters with no previous photometry. The finding charts for the giants in these latter clusters are given in the appendix. This IR photometry is discussed in the next chapter.

For the fiber runs (MX and Argus), accurate positions of cluster giants were measured ahead of time with the Grant machine at KPNO headquarters. Dr. B. N. Suntzeff kindly provided accurate positions for some of the clusters measured with Argus. As indicated in table 3, the sources of photometry for these clusters are given by Suntzeff et al. (1992)

2.3. Spectroscopic Observations

All the standards were taken with widely different S/N, from very high to that of our worse program stars, which allowed a better determination of the true errors involved in the abundance and RV determinations.

3.1. Argus

During 2 nights in August 1992 we took spectra of a few hundred cluster and bulge giants with the Argus multifiber spectrograph at the CTIO 4 m telescope. The nights were not photometric, occasional cirrus interrupted the observations from time to time. The bulge fields and globulars close to the Galactic center were up for the first part of the night. The rest was devoted to observations of open and globular clusters. With Argus we used the bench spectrograph with the 632-line grating KPGL1 blazed at 4200 Å. This setup gives ~ 2.5 Å

resolution, leading to velocities accurate to ≤ 12 km/s, and with enough S/N for reliable abundance estimates. The exposure time was ~ 40 min, about 20 fibers produced good S/N spectra per fiber configuration. The fields were observed above 1.5 airmasses, during bright time. A HeAr comparison lamp was taken immediately after each object exposure. The spectral coverage is from 4700 to 5700 Å. With Argus we observed a variety of giants in globular and open clusters that are used as metal abundance and luminosity standards. Several cluster radial velocity standards were observed in 47Tuc, NGC 1851, NGC 288, and NGC 362 to reduce to the standard velocity system.

The exposure times for the giants in the standard open and globular clusters ranged from 10 to 15 minutes. The giants in the clusters located in the Galactic bulge required longer exposures, typically 30 minutes. The spectrograph is stable enough that it was not necessary to take lamps before and after each cluster, as tested in a couple of clusters.

2.3.2. MMT + Red Channel

The spectra obtained at the Multiple Mirror Telescope (MMT) with the Red Channel spectrograph in 2 bright nights in July 1989 and 2 nights in July 1992 have a spectral coverage from 4600 to 5350 Å. We used the 800×800 TI CCD chip and an 800-line grating in 2nd order blazed at 5000 Å, the resulting resolution was ~ 1.8 Å. The bulge globulars were observed at high airmasses, ranging from 1.5 to 2.5. HeNeAr comparison lamps were taken immediately after each object exposure. Typical exposure times were between 20 and 30 minutes.

The slit size projected on the sky is 1.5×180 arcsec. We have selected typically 2–3 stars aligned on the sky, and rotated the instrument to accommodate them on the slit at the same time. The seeing varies between 1 and 2 arcsec. The exposures were long enough, that the 5 MMT mirrors needed stacking after every 1-2 exposures. This ensured that the stars were varied in position in the slit, so as not to bias the radial velocities, as confirmed by multiple exposures. Even though the standards required very short exposures, it was possible to center them carefully, so that gross velocity errors were also avoided. In each of the MMT and 90" runs we observed between 3 and 5 RV standards from the IAU lists, usually recorded at the beginning, middle and end of the night.

2.3.3. Steward 90" + MX

The observations at the Steward Observatory 90" telescope with the MX multi-fiber spectrograph (Hill and Lesser 1986, 1988) were taken during 3 good nights in June 1990 and 3 fair nights in July 1990. MX is a multifiber spectrograph with automatic positioning that allows us to obtain spectra for 32 stars at a time. We used the 800×800 TI CCD chip and an 1200 line grating in 2nd order blazed at $5200 \text{ \AA}$, obtaining a dispersion of $0.98 \text{ \AA/pix}$ and a resolution of $\sim 2 \text{ \AA}$. For a scale of $0.75''/\text{pixel}$ the width of the fibers is equivalent to about 170 km/s . The spectral coverage is from 4550 to $5400 \text{ \AA}$. Due to the nature of MX fiber selection algorithms, several program stars were observed twice and a few three times on different nights. All standard stars were observed in many fibers to take into account possible fiber-to-fiber errors. The exposure times for

the program stars ranged from 20 to 35 minutes. In this run we concentrated on bulge giants, and observed only clusters that give good velocity standards (M4, M3).

2.3.4. Steward 90" + B&C

The Steward Observatory 90" telescope with the B&C Spectrograph was used in 2 nights in May 1992 to observe the brighter bulge globulars. The same detector and grating as with MX was used, achieving similar resolution and wavelength coverage. A long slit of $1.5'' \times 180''$ allowed us to observe 2 or more stars at a time in a single exposure. The exposure times ranged from 30 to 50 minutes. The airmasses also ranged from 1.5 to 2.5.

2.4. Reductions

We have performed the reductions for all the observing runs using the Interactive Reduction Astronomical Facility (IRAF). Even though most of the IRAF routines are capable of doing the reductions automatically after the critical parameters have been set, we have performed every step of the reduction for every single spectrum interactively. The CCD reduction for all the data was similar, following standard procedures within the IRAF environment, with the routines in the package CCDRED. The CCD frames were overscan and bias subtracted, and trimmed to remove the unused parts of the images. Then they were divided by a high signal to noise (S/N) flat-field (dome quartz lamp) that was previously normalized by fitting a high order surface, leaving only the

pixel to pixel response. The next steps in the reductions differ according to the instrument used, and we will describe them in turn.

2.4.1. Argus

The Argus reductions were done following the precepts of Suntzeff et al. (1993). These authors extensively describe the reduction procedure followed here, consequently, we will give only an outline. The spectra were extracted in IRAF within the ARGUS package, following the recipes kindly provided by Dr. N. Suntzeff. First, the spectra for all apertures were traced with a low order spline function using a high S/N flat field. With that frame, we defined the width of the aperture windows to enclose all of the star light. Then, the objects, skies and comparison lamps were extracted into one dimensional spectra. The fibers were corrected to give uniform transmission using a very high S/N sky exposure. The one dimensional spectra were wavelength calibrated interactively and rebinned to the same dispersion and wavelength coverage. The sky subtraction was also done interactively, and locally, medianing the nearby 4 fibers to account for local focus changes. The subtraction of the sky scaled by the exposure time sometimes did not completely account for the sky line at $5577.5 \text{ \AA}$. In these cases (which were never greater than 10 % in the sky counts), the sky was scaled properly until the residual $5577.5 \text{ \AA}$ line disappeared. Particular care was taken at that point because any residual emission line would bias the radial velocity determinations, more so for the low S/N spectra. For all the program stars no extinction correction or flux calibration was attempted. However, the

sky spectra were checked to see that there were only a few percent continuum variations from fiber to fiber.

2.4.2. MMT + Red Channel and 90" + B&C

The Red Channel data reduction was summarized in Minniti et al. (1992). The data from these two instruments were similar: 2 dimensional spectra with slit length of 3 arcmin, and about 800 Å coverage, centered at 5200 Å. The background sky counts are high in most cases, because these were bright nights. The spectra were traced and extracted to one dimension using the TWODSPEC package in IRAF. First we trace the object spectra (typically 2–3 per frame) interactively with a low order spline, and by defining a window that would enclose all the star light. At the same time the sky subtraction was performed taking two 10 pixel wide windows on either side of the stellar spectrum. The selection of these windows was chosen interactively for each single spectrum, to avoid including faint stars of these crowded fields. In general, the sky subtraction was cleaner with the slit than with the fiber spectra. The arc exposures were extracted following the same trace, with the sky subtraction switch off. About 20–30 lines of the comparison lamps were identified in one high S/N spectrum. That spectrum was used as reference to reidentify the lamps corresponding to every object, and the wavelength solution obtained using a low order spline function. The spectra were placed on a linear wavelength scale. The one dimensional spectra were then checked for cosmic rays. The cosmic rays were interpolated over interactively. There are 2 sky emission lines in the region covered, and the sky subtraction worked very well at removing them.

2.4.3. Steward 90" + MX

The MX data reduction was also described by Minniti et al. (1992), The MX spectra were extracted in IRAF with the MXPACAGE written by J. Hill for the IRAF environment. Ultimately, 1 dimensional spectra which were wavelength calibrated, sky subtracted, and rebinned to the same dispersion were produced.

We traced the spectra for all apertures with a low order spline function using a high S/N twilight exposure. That frame also defined the width of the aperture windows to enclose all of the star light. Then, the objects, skies and comparison lamps were extracted into one dimensional spectra. The fibers were corrected to give uniform transmission using a very high S/N sky exposure. The one dimensional spectra were wavelength calibrated interactively and rebinned to the same dispersion and wavelength coverage. The sky subtraction was also done interactively, medianing the sky fibers. The subtraction of the sky scaled by the exposure time sometimes sometimes needed small scale corrections ($\leq 10\%$) to account for the emission lines. As with the Argus reductions, particular care was taken with the sky subtraction because any residual emission line would bias the radial velocity determinations, more so for the low S/N spectra. For all the program stars no extinction correction or flux calibration was attempted. However, the sky spectra were checked to see that there were not more than a few percent continuum variations from fiber to fiber.

2.5. Velocity Determinations

We will discuss the velocity determinations first, since they will help us eliminate some field stars when doing the metallicity calibration.

2.5.1. Argus Velocities

The Argus radial velocities were determined using the cross correlation technique (Tonry and Davis 1979, see also Timkin 1971) using the package RVEL within IRAF. The spectra are extracted on a logarithmic scale of 1024 channels, flattened by fitting a 4th order polynomial and masked over the edges with a cosine bell to minimize ringing. Then the noise at frequencies higher than the resolution and much lower than the broadest spectral features were filtered away. The velocity shifts relative to the standard star templates were determined by fitting parabolas to the upper 50 % of the cross correlation peak. For $S/N \sim 10$ the R parameter of Tonry and Davies (1979) turns out to be ~ 8 . Stars with $S/N \leq 10$ are not considered because the errors in velocities are greater than ~ 20 km/s. The R parameter is a measure of the error in the radial velocity determined by cross correlations, and is defined as the height of the correlation peak with respect to the neighbouring noise peaks.

For the Argus run, we adopted the standard giants in clusters chosen by Suntzeff et al. (1991, and references therein). The zero point between the two Argus nights was chosen to be the mean velocity of 47Tuc. The twilight sky was not used as standard for the radial velocity measurements, for the reason discussed below. However, the velocity of the sky in the different fibers was computed as an extra check on the wavelength solutions and the accuracy of

the velocities. The velocity dispersion of the sky measured in the different fibers is $\sigma = 4.5$ and 5.6 km/s for the first and second Argus nights, respectively.

2.5.2. MMT AND 90" Velocities

For the MX and early MMT data, the radial velocities were determined doing cross correlations using the package MARSXC, written by J. Hill and J. Eisenhamer. Measuring the radial velocity of a typical standard star in all different fibers yields $\sigma = 2.3$ km/s. All the radial velocities for the MX data were referred were independently correlated with the nightly standards and twilight sky. The same procedure was repeated for the Red Channel data. The differences in velocities for the standards determined in the different nights were always less than 10 km/s. The errors involved in the determination of the velocities were checked by plotting the difference in velocities obtained for same stars observed in different nights with MX versus the S/N. The stars with $S/N \geq 5$ per pixel repeat very well, the lower S/N spectra will not be considered here.

We have also taken MX spectra of about 21 stars in the globular cluster M3 with well known radial velocities (from Pryor, Latham and Hazen 1986) for each of the 4 MX nights.

For the MMT and 90" runs, radial velocity standards from the IAU lists were measured. Typically, 4 to 6 standards were observed nightly, plus the solar spectrum of the sky. The zero point shifts were determined by the nightly velocity of HD112299, which was observed in all the runs. The choice of other

zero points (e.g. the mean of all the standard velocities or the twilight sky) does not produce different results. We have decided not to use the twilight sky as a radial velocity standard. This is because any residual sky left from the sky subtraction would bias the velocities more when is correlated with the sky spectrum itself (particularly important for the low S/N spectra). The observations at the MMT and 90" telescopes were carried out at high airmasses (between 1.5 and 2.5), where the telescope and spectrograph suffer more flexures. The velocities of standards, however, do not reflect any trend with airmass.

2.5.3. Cluster Membership

For the velocity determination of clusters, it is preferable to have several spectra of individual giants. However, in very crowded fields, it is difficult to separate cluster members from field stars, more so for metal rich clusters, which match the metallicity of the bulge giants. In such cases where the clusters are concentrated, integrated spectroscopy can give a better answer.

Membership in the bright standard clusters was confirmed for almost all the giants. The clusters of the Galactic bulge, however, showed a significant fraction of non-members. The percentage of non-members increases for the globulars closest to the Galactic center, being up to 50% for Pal6, HP1 and N6440.

We note that globulars have intrinsic velocity dispersions typically between 5 and 10 km/s (Pryor & Meylan 1993). For the clusters observed here, the intrinsic dispersion is small compared with the errors in the velocities. In general, these intrinsic velocity dispersions do not affect our estimate of the error in the mean velocity, except in cases like 47Tuc ($\sigma = 9.7$ km/s) or M22 ($\sigma = 8.3$ km/s).

2.5.4. Velocity Errors

Here we will describe repeated velocity determinations in clusters with many giants observed on different nights with Argus, MX, and Red Channel, respectively. By these means, the intrinsic and nightly zero point errors are checked for each of these runs.

2.5.4.1. Argus: Repeated measurements in 47Tuc.

Table 4 lists the individual and mean radial velocities and Mg indices for stars in 47Tuc that had at least 3 spectra taken in two different nights, with their respective errors. The measurements listed in columns 2 to 9 are from individual Argus setups. There were 2 different setups observed per night. These did not necessarily include the same stars, only a subset of the fibers included repeated stars. The typical dispersion in the mean velocities is ~ 6 km/s. The typical dispersion in the Mg indices is 0.03. The velocity dispersion of 47Tuc computed from the mean velocities of the individual stars is $\sigma = 10.86$ km s⁻¹. If the intrinsic velocity dispersion of 47Tuc is 8.8 km/s (e.g. Mayor et al. 1984), then the errors in our velocities have a dispersion $\sigma = 6.4$ km/s.

These values are conclusive in showing that the dispersion observed for the 47Tuc giants in the Mg+2Fe vs B-V diagram is not entirely due to measurement errors. The intrinsic dispersion in the index strength is real.

Table 2.4: Individual velocities and Mg Indices for 47Tuc Giants

Star	V1	V2	V3	V4	Mg1	Mg2	Mg3	Mg4	<V>	<Mg>
w206	-6.4	1.2	-12.3	0.2	1.23	1.16	1.08	1.12	-4.3+6.3	1.10+0.06
2016	-17.5	-5.7	-13.9	2.0	1.13	1.19	1.12	1.15	-8.8+8.7	1.13+0.03
2030	-8.3	6.4	-11.9	16.0	1.13	1.11	1.07	1.08	0.6+13.0	1.09+0.03
1005	-12.8	-4.3	-6.6	1.4	1.11	1.16	1.08	1.12	-5.6+5.9	1.11+0.03
w115	-11.1	-7.0	-19.0	-1.1	1.09	1.09	1.05	1.05	-9.6+7.5	1.06+0.02
3010	-46.1	-37.0	-22.4	-19.5	1.04	1.15	1.03	1.06	-31.3+12.5	1.04+0.05
426	-25.4	-28.7	-13.3	...	1.18	1.11	1.10	...	-22.5+8.1	1.11+0.04
410	-26.1	-27.2	-19.4	...	1.14	1.12	1.11	...	-24.2+4.2	1.12+0.01
559	-30.3	-26.4	-27.9	...	1.15	1.11	1.08	...	-28.2+2.0	1.10+0.03
431	-23.4	-11.3	-24.3	...	1.15	1.15	1.06	...	-19.7+7.3	1.10+0.05
484	-3.5	-2.2	-10.4	...	1.06	1.08	1.06	...	-5.4+4.4	1.06+0.01
390	-18.1	-15.7	-17.2	...	1.07	1.14	1.05	...	-17.0+1.2	1.06+0.05
355	-35.7	-27.6	-34.5	...	1.01	1.02	1.03	...	-32.6+4.4	1.02+0.01
341	-22.0	-5.7	-10.0	...	1.03	0.98	0.96	...	-12.6+8.4	0.98+0.04
55	-25.2	-22.2	-18.6	...	1.06	1.10	1.07	...	-22.0+3.3	1.03+0.07
371	-21.8	...	-23.3	-11.0	1.03	...	1.00	0.97	-18.7+6.7	1.00+0.03
w221	-10.2	...	80.7*	0.1	1.01	...	0.96	1.01	-5.1+7.3	0.99+0.03
w125	-23.6	...	-6.8	35.9	0.94	...	0.96	0.89	2.8+30.3	0.94+0.04

Notes to table 4:

* = measurement discarded.

2.5.4.2. MX: Repeated measurements in M3

Repeated observations of about 10 giants in M3 were obtained on four different nights. These giants have accurate velocities from Pryor, Latham & Hazen (1988). M3 is a metal poor cluster, so the giants have weak lines, and the velocity errors will be larger than expected for more metal rich giants. Table 5 lists the individual velocities (from cross-correlation with 3 IAU velocity standards observed each night), and Mg index strength for the giants in M3 measured in different nights, as well as the mean nightly velocity of M3. Only spectra with $S/N \geq 5$ are considered. The mean nightly velocities of M3 are computed using all the giants observed, not just the ones with repeated measurements listed in table 5. These mean velocities reveal that there are no gross zero point errors per fiber setup or per night. The mean velocity of M3 from 39 independent spectra is $V_{M3} = -156 \pm 5$ km/s. For our stars, we should have found $V_{M3} = -148 \pm 3$ km s⁻¹. The difference is less than 1.5σ , and well within our estimate of the zero point error with respect to the standard system.

Also, from the multiple spectra of M3 giants we confirm that there are no systematic effects between the Mg indices from different fiber setups and different nights. The mean difference between nights is $\Delta_{Mg} \approx 0.02$, and each individual measurement has an associated error $\sigma_{Mg} = 0.03$.

Finally, MX also has a very efficient observing routine that allows us to place a bright standard in different fibers in ~ 5 minutes total time. We took advantage of that, measuring radial velocities for 4 IAU velocity standards in different fibers. The agreement between fibers is excellent ($\sigma = 3$ km s⁻¹).

Table 2.5: Individual velocities for M3 Giants

Star	V1	V2	V3	V4
164	...	-197	...	-180
194	-149	-150	-147	-169
192	-155	-160	...	-159
1270	-165	-176	...	-158
837	-151	-150	...	-155
1392	-155	-151	-144	-188
281	-146	-151	-145	-149
1397	-143	-146	...	-164
1208	-163	-150	...	-139
Mean	-153	-159	-151	-162
O	8	17	15	14
N	10	10	9	10

Notes to table 5:

- Only stars with $S/N > 5$ considered.
- Star IDs from Pryor et al. (1988).

Furthermore, no systematics were found, i.e. no fiber gave a systematically high or low velocity.

2.5.4.3 Red Channel: Repeated measurements in M4

As we did for the fiber systems, here we will discuss some repeated measurements of giants in M4 taken with the MMT + Red Channel, and the 90" + B&C spectrographs in different nights. About 5 giants with good velocities from Peterson & Latham (1986) were observed in different nights. Some of these giants were used as radial velocity standards as well, but we have also cross-correlated these giants against IAU velocity standards only (typically 3–4 per night). The mean velocity obtained for M4 is $V_{M4} = 65 \pm 10$ for all the giants observed in all the nights. This value agrees very well with $V_{M4} = 70 \pm 4$ km s⁻¹ from the compilation of Pryor & Meylan (1993).

The Mg indices also repeat very well, and there is a small systematic shift between the MMT and 90" spectra, in the sense that we have to add $\Delta_{Mg} = 0.03$ to the MMT indices to refer them to the MX and B&C system.

2.5.5. Comparison with Previous Cluster Velocities

We have obtained independent velocities for several clusters with unknown or uncertain velocities. The mean heliocentric velocity for the clusters, along with their observed (uncorrected for observational errors) associated velocity dispersions are listed in column 3 of table 6. Note that these quoted errors do not include a possible zero point error of ~ 10 km s⁻¹ for the whole system.

Table 2.6 : RADIAL VELOCITIES

Cluster	[Fe/H]	$\langle V \rangle$	N	V_{ref}	Phot	Reference	Co
N2141	-0.60	13 $\pm$ 15	15	53	BV	FJ93	
N2158	-0.58	14 $\pm$ 9	20	22	BV	FLJ89	
N2204	-0.58	69 $\pm$ 9	14	93	BV	FLJ89	
N2243	-0.56	61 $\pm$ 15	12	62	BV	FJ93	
N2477	-0.05	3 $\pm$ 3	17	7	BV	FJ93	
N2506	-0.52	68 $\pm$ 8	20	87	BV	FJ93	
N6819	0.05	0 $\pm$ 7	7	-5	BV	FJ93	
N6791	0.23	-45 $\pm$ 7	5	-50	BV	FJ93	
47tuc	-0.71	-17 $\pm$ 10	47	-17	BV	A89,M+84	1
N288	-1.40	-62 $\pm$ 17	15	-47	BV	A89,HSM86	
N362	-1.28	200 $\pm$ 25	15	217	BV	A89,HSM86	
N1851	-1.29	311 $\pm$ 16	15	318	BV	A89,AZ88	2
M3	-1.66	-156 $\pm$ 5	18	-141	BV	A89,HSM86	
N5466	-2.22	...	2	120	BV	A89,HSM86	
M4	-1.20	65 $\pm$ 10	18	61	IR	A89,S+93,HSM86	
N6325	-1.44	...	2	8	IR	A89,HSM86	
N6356	-0.56	56 $\pm$ 20	14	37	IR	A89,AZ88	2
N6366	-0.99	-116 $\pm$ 9	3	-123	BV	A89,DS89	
N6401	-1.01	-78 $\pm$ 33	13	-62	IR	W85,HSM86	
N6402	-1.39	...	4	-25	BV	A89,HSM86	3
N6440	-0.34	-43 $\pm$ 22	5	-83	IR	A89,HSM86	3
N6517	-1.34	-17 $\pm$ 28	4	-37	IR	A89,HSM86	
N6528	-0.23	203 $\pm$ 20	7	189	IR	A89,AZ88	2,3
N6553	-0.29	46 $\pm$ 22	6	-24	BV	A89,HSM86	
N6624	-0.37	34 $\pm$ 27	28	55	BV	A89,HSM86	
N6637	-0.59	23 $\pm$ 27	14	31	BV	A89,HSM86	3
M71	-0.58	-37 $\pm$ 10	3	-31	BV	A89,HSM86	
HP1	-0.50	60 $\pm$ 13	4	44	IR	A89,AZ88	
Pal6	0.22	201 $\pm$ 20	3	0	IR	W85,HSM86	
M28	-1.30	32 $\pm$ 15	10	-2	IR	A89,HSM86	
N6642	-1.30	-41 $\pm$ 24	5	-47	IR	W85,HSM86	
M22	-1.75	-159 $\pm$ 11	15	-164	IR	A89,HSM86	
M15	-2.25	-109 $\pm$ 26	4	-100	BV	A89,HSM86	

Notes to Table 1:

A89 = Armandroff (1989), FJ92 = Friel & Janes (1993), FLJ = Friel, Liu & Janes (1989), W85 = Webbink (1985), S+93 = Suntzeff et al. (1993), AZ88 = Armandroff & Zinn (1988), HSM86 = Hesser, Shawl, & Meyer (1986), M+84 = Mayor et al. (1984), DS89 = DaCosta & Seitzer (1989).

1. Cluster used as zero point for ARGUS observations.

2. Clusters noted as discrepant by AZ89.

3. Clusters noted as discrepant by HSM86, where $\Delta V \geq 40 \text{ km s}^{-1}$

The number of giants members taken into account to compute the mean velocities is listed in column 4. Column 5 gives the best available velocity determination for the clusters. The values from the compilation of Pryor & Meylan (1993) are preferred, otherwise we use the values from Armandroff & Zinn (1988, hereafter AZ88) or Hesser, Shawl, & Meyer (1986, hereafter HSM86).

The real velocity dispersions for each cluster can be obtained by subtracting in quadrature the observational errors ($\sigma_{obs} = 6.5$ km/s) to the observed velocity dispersions listed in column 3 of table 6. The observed values are listed in that column because these are the values that one should use to decide membership to the cluster. We note that otherwise, no conclusions should be drawn about the intrinsic velocity dispersions of the clusters themselves, because the velocities are simply not precise enough (except for 47Tuc, where repeated measurements are available).

The velocities in column 3 of table 6 can be compared with the lists of Pryor & Meylan (1993), HSM86 and AZ88 for the globular clusters, and with the results of Friel & Janes (1993) for the open clusters. In general, for the globular clusters the agreement is very good. The mean difference between Pryor & Meylan (1993) and us is 6.0 km/s, with an rms scatter of 9.3 km s^{-1} for 10 clusters in common. The mean difference between AZ88 and us is -5.2 km/s , with an rms scatter of 8.5 km s^{-1} for 4 clusters in common. The mean difference between HSM86 and us is -7.0 km/s , with an rms scatter of 23 km s^{-1} for 20 clusters in common.

For the open clusters there is a systematic velocity difference between Friel & Janes (1993) and us, in the sense that our velocities are 10 km/s smaller,

with an rms scatter of 15 km s^{-1} , for 8 clusters in common. This difference is higher than for the globulars, but still within the combined error bars of both systems, and within the estimate of the zero point errors. The velocities for all the opens but 2 come from Argus spectra. The exceptions are NGC6819 and NGC6791, which were observed with MX.

We note that our velocities of HP1 and Pal6 are more uncertain, and should be taken with caution. A few globular clusters whose published velocities are discrepant, as noted by AZ88 and HSM86, are marked on table 6. Our new measurements help to improve these determinations. There is one cluster with no previously published velocities: Pal6. Even though we observed only a few giants, and with low S/N in the case of Pal6, these velocities should be good to $\sim 15 - 20 \text{ km/s}$. For a few clusters our values differ from those previously published. For the open cluster NGC2141, we get a velocity that is 41 km/s lower than that of Friel & Janes (1993). Our measurement of velocity for NGC6356 agrees with the value of AZ88, and is substantially higher than the HSM86 velocity. For NGC6440, our velocity value is closer to that of Zinn & West (1984), lower than that of HSM86. The velocity of NGC6528 is in good agreement with the values of AZ88 and HSM86, confirming than the Webbink (1985) velocity is much too low. The velocity of NGC6637 obtained here agrees with HSM86, confirming their results that the value of Mayall (1964) is much too low. The most discrepant of our velocities is NGC6553, which is 74 km/s higher than that published by HSM86. The value of Zinn & West (1983) is closer to our velocity (-5 km/s), but still in disagreement. We have measured several giants in this

cluster, and the mean cluster velocity seems to be well defined. We have not found anything wrong with this determination, but the Zinn & West value should be preferred because it is closer to the independent determinations of Mayall (1946), and HSM86. NGC6553 is a target for better velocity measurements, it is not a very faint cluster.

2.6. The Abundance Determinations

We are faced with the problem of defining a calibration grid to derive abundances for the bulge giants. For each giant we have to know the dependence of metallicity on gravity, temperature, and, as discussed below, on age and detailed chemical history.

Perhaps the bigger problem is to determine the chemical history of the calibrators and the giants for which the calibration is applied. For example, Friel & Janes (1993) find that the metallicities for open clusters derived from similar Mg and Fe indices depend on the age of the cluster. This is possibly due not only to different masses, but also due to variations in relative abundances of Mg with respect to Fe. Gorgas et al. (1993) also pointed out a systematic – unexplained – difference between the indices of the field stars and globular cluster stars. To avoid confusion, we will assume that the detailed abundances for halo stars follow the trends discussed by Wheeler, Sneden & Truran (1991), while the disk stars follow the trends found by Edvardsson et al. (1993). Therefore, the globular cluster population is treated separately from the open cluster and field star population.

There are 3 approaches for the determination of metallicities in medium-resolution spectra: comparison with a grid of model atmospheres (e.g. Barbuy et al. 1992, 1993, Gulati et al. 1993), cross correlations against standard star templates (e.g. Ratnatunga & Freeman 1988), and calibration of spectral indices (e.g. Burstein et al. 1983). The first approach of model atmospheres is the most promising for the future. It is desirable however, that the spectra be of higher resolution and S/N. Unfortunately, the construction of a grid for the relevant space of parameters proper for bulge giants is not reliable especially for the cooler and most metal rich giants, but in the near future this is the way to proceed. More than 1/3 of our sample giants have high enough S/N to pursue this avenue in the future. The second approach of cross correlations is found to be very dependent on S/N, one needs a dataset with high and uniform S/N, otherwise the metallicity derived is biased. Finally, spectral indices have the advantage that they are empirically calibrated against a similar stellar population, and one has the freedom to choose the location and width of the passbands to recover the best abundance indicators. Thus, for lower S/N spectra one can choose wider passbands. These spectral indices can also be compared with the predictions of different sets of models atmospheres.

To obtain luminosity classifications and metallicity estimates we define a set of spectrophotometric indices of line intensities following Faber *et al.* (1985) and Friel (1988). The spectra were converted to text files for the evaluation of the different spectrophotometric indices using our own software. Each index is defined as the ratio of the average flux in the central feature passband to that

of the continuum passbands located at the sides, and it is expressed in terms of magnitudes. The indices were measured in the rest frame of the star, geocentric velocity corrections were made to the passbands.

This is important, because some of the clusters have velocity moduli in excess of 100 km/s, which would represent a significant portion of some of the passbands used in the indices.

A set of 7, 7 and 5 indices are measured for the MX, Argus, and MMT data, respectively. Their bandpasses are defined in Table 7, as well as the species measured and criteria. The indices Fe4680, Fe5335, and Fe5400 for the MMT spectra, the index Fe5400 for the MX spectra, and the index Fe4680 for the Argus spectra were not measured because they fell out of the wavelength range covered.

Listed in table 8 are the spectrophotometric indices measured for all the standard stars with $S/N \geq 10$ observed at the 90" and MMT. Also listed are the $(B-V)_o$, spectral types and $[Fe/H]$. Since we have used the same indices as Friel (1988), a direct comparison is possible for the standards in common both for MX and MMT runs (we did not observe any of Friel's standards with Argus). For the standards in common, the rms difference between the same indices are: $\sigma(Mg) \sim 0.04$, $\sigma(Fe4680) \sim 0.03$, $\sigma(Fe4920) \sim 0.03$, $\sigma(Fe5011) \sim 0.04$, $\sigma(Fe5270) \sim 0.03$, $\sigma(Fe5335) \sim 0.02$. Table 9 lists the indices measured for the giants observed with Argus. Table 10 lists magnitudes, colors, radial velocities and $MG+2Fe$ for the same stars.

The spectroscopic indices for the different telescopes and instrument setups agree with each other, provided small zero point offsets are applied. These shifts

Table 2.7: DEFINITION OF SPECTRAL INDICES

INDEX	CENTER	CONT. 1	CONT. 2	SPECIES	CRITERION
Mg	5130.0-5200.0	4935.0-4975.0	5303.0-5367.0	Mgb+MgH	lum-met
Mg1	5071.0-5134.7	4897.0-4958.2	5303.0-5366.7	MgH	lum-met
Mg2	5156.0-5197.2	4987.0-4958.2	5303.0-5366.7	Mgb	lum-met
Mgb	5162.0-5193.2	5144.5-5162.0	5193.2-5207.0	Mgb	lum-met
MgH	5200.0-5212.0	4897.0-4958.2	5303.0-5366.7	MgH	lum-met
H β	4845.0-4875.0	4829.5-4848.2	4878.0-4892.0	H,FeI	temp
Fe4680	4636.0-4723.0	4606.0-4636.0	4736.0-4773.0	FeI,CrI,NiI,MgI	met
Fe4920	4900.0-4940.0	4796.0-4841.0	4935.0-4975.0	FeI	met
Fe4980	4975.0-4989.0	4935.0-4975.0	5051.0-5096.0	FeI	met
Fe5011	4976.0-5051.0	4935.0-4975.0	5051.0-5096.0	FeI,FeII,NiI,TiI	met
Fe5270	5248.0-5287.0	5220.0-5250.0	5288.0-5322.0	FeI,CaI	met
Fe5335	5315.0-5353.0	5308.0-5317.0	5356.0-5460.0	FeI,CrI	met
Fe5400	5384.0-5430.0	5356.0-5364.7	5430.0-5460.0	FeI	met

are: $\Delta Mg = 0.04$, $\Delta Fe5270 = 0.00$, and $\Delta Fe5335 = 0.02$, in the sense Argus minus MX or MMT. The MX and MMT scales have the same zero point. Note that these zero point offsets are of the order or smaller than the scatter in the index measurements.

The mean errors in radial velocities and spectrophotometric indices derived from comparison of repeat observations is given by $\sigma = 0.88 \times \langle Vr_1 - Vr_2 \rangle$ (e.g. Pier 1983). In summary, for the MX and MMT data, relative velocities are good to ~ 7 km/s rms, the absolute velocities to ~ 10 km/s, and the errors in the spectral indices to be $\sigma(Mg) = 0.05$, $\sigma(Fe4680) = 0.04$, $\sigma(Fe4590) = 0.04$, $\sigma(Fe4920) = 0.04$, $\sigma(Fe5011) = 0.05$, $\sigma(Fe5270) = 0.04$, and $\sigma(Fe5335) = 0.03$ for the spectra with $S/N \geq 5$. For the Argus data, relative velocities are good to ~ 9 km/s rms, the absolute velocities to ~ 12 km/s, and the errors in the spectral indices to be $\sigma(Mg) = 0.05$, $\sigma(Fe4680) = 0.04$, $\sigma(Fe4590) = 0.04$, $\sigma(Fe4920) = 0.04$, $\sigma(Fe5011) = 0.05$, $\sigma(Fe5270) = 0.04$, and $\sigma(Fe5335) = 0.03$ for the spectra with $S/N \geq 8$. We stress that even when the instrumental setups and the calibrations were different, the good agreement supports the accuracy of the data.

The scatter of the indices of individual stars within a cluster around the mean for the cluster are consistent with these values, although it is clear that the scatter increases for increasing metallicity. This effect is not due to observational errors, since the spectroscopic indices should be better measured for the metal rich stars with stronger features, but it is due to the onset of molecular absorption, in particular MgH. Stars of the same iron abundance (i.e. stars

Table 2.8 : STANDARD STARS

Star	B-V	ST	[Fe/H]	Mg	H β	Fe46	Fe49	Fe50	Fe52	Fe53
HD102328	1.27	K3III	0.44	1.04	0.82	0.92	0.78	0.82	0.90	0.84
HD107328	1.16	K1III	-0.47	0.97	0.82	0.84	0.79	0.81	0.85	0.79
HD112127	1.27	K2III	-0.09	1.05	0.84	0.95	0.81	0.81	0.87	0.83
HD117876	0.96	K0III	-0.41	0.87	0.84	....	0.69	0.78	0.81	0.77
HD171779	1.12	K0III	-0.04	0.78	0.88	0.89	0.78	0.79	0.80	0.82
HD167042	0.94	K1III	-0.06	0.87	0.88	0.86	0.80	0.79	0.81	0.80
HD168322	1.00	K0III	-0.33	0.82	0.88	0.86	0.78	0.79	0.79	0.78
HD180928	1.43	K3III	-0.48	1.00	0.89	0.90	0.78	0.89	0.83	0.84
HD188056	1.28	K3III	0.29	0.98	0.91	0.95	0.74	0.79	0.84	0.85
HD191046	1.16	K0III	-0.50	0.86	0.84	0.83	0.74	0.78	0.81	0.84
HD198809	0.82	G7III	-0.16	0.74	0.87	0.85	0.76	0.80	0.81	0.85
HD221148	1.08	K3III	0.55	0.94	0.87	0.89	0.77	0.81	0.82	0.92
HD221345	1.02	K0III	-0.24	0.80	0.84	0.85	0.76	0.82	0.80	0.86
HD98061	1.15	K2III	....	0.95	0.81	....	0.73	0.82	0.87	0.87
HD171232	0.95	G8III	....	0.78	0.86	....	0.72	0.79	0.80	0.81
HD194071	0.95	G8III	....	0.89	0.84	....	0.73	0.82	0.84	0.83
HD213947	1.42	K4III	....	1.04	0.77	....	0.81	0.82	0.87	0.88
HD223094	1.52	K5III	....	1.06	0.78	....	0.66	0.82	0.87	0.87
HD108225	0.95	G8III-IV	0.01	0.89	0.83	0.86	0.80	0.80	0.85	0.79
HD182572	0.78	G8IV	0.37	0.89	0.87	0.87	0.76	0.79	0.82	0.84
HD217014	0.67	G3IV	0.08	0.82	0.90	0.83	0.79	0.81	0.80	0.79
HD117176	0.71	G5IV-V	-0.16	0.85	0.87	....	0.70	0.77	0.79	0.76
HD104556	0.86	G9IV-V	-0.64	0.93	0.79	0.82	0.77	0.79	0.85	0.79
Sun	0.65	G2V	0.00	0.88	0.88	....	0.82	0.82	0.80	0.82
HD112299	0.52	F8V	....	0.83	0.92	....	0.72	0.78	0.79	0.73
HD140913	0.58	G0V	....	0.80	0.91	....	0.70	0.77	0.78	0.75
HD149803	0.50	F7V	....	0.78	0.93	....	0.53	0.79	0.79	0.80
HD131511	0.83	K2V	....	0.95	0.88	....	0.73	0.80	0.82	....
HD131977	1.11	K4V	....	1.15	0.82	....	0.72	0.79	0.87	....
HD136442	0.90	K0V	....	1.03	0.88	....	0.73	0.81	0.84	....
HD186408	0.64	G3V	0.21	0.77	0.92	0.83	0.74	0.77	0.78	0.78
HD186427	0.66	G4V	0.09	0.80	0.94	0.82	0.74	0.76	0.78	0.77
HD201091	1.17	K5V	-0.05	1.18	0.78	0.78	0.72	0.79	0.84	0.91
HD219134	1.00	K3V	0.02	1.13	0.81	0.84	0.80	0.81	0.86	0.86
HD224930	0.67	G2V	-0.67	0.81	0.84	0.79	0.75	0.80	0.77	0.84
61Cyg A	1.18	K5V	....	1.21	0.79	....	0.69	0.79	0.84	....
61Cyg B	1.37	K7V	....	1.14	0.76	....	0.64	0.80	0.84	....
N6819*258	1.18	gM	-0.10	1.02	0.89	0.78	0.53	0.90	0.81	0.81
N6819*20	0.94	gK	-0.10	0.90	0.92	0.86	0.83	0.82	0.85	0.80
N6819*142	0.84	gK	-0.10	0.84	0.93	0.87	0.82	0.82	0.85	0.81
N6819*11	0.91	gK	-0.10	0.93	0.97	0.87	0.82	0.82	0.86	0.76
N6819*485	1.28	gK	-0.10	1.03	0.90	0.87	0.80	0.83	0.86	0.83
N6819*352	1.17	gM	-0.10	0.87	1.15	0.90	0.31	1.48	0.84	0.77
N6819*19	1.00	gK	-0.10	0.85	0.90	....	....	....	....	....
N6819*A	....	gK	-0.10	0.97	0.94	0.53	0.72	0.88	0.88	0.69
N6819*B	....	gK	-0.10	0.77	1.02	0.79	0.81	0.76	0.77	0.81
N6791*2008	1.42	K4III	0.05	1.11	0.88	....	0.57	0.86	0.82	....
N6791*2044	0.92	K1IV	0.05	1.01	0.88	....	0.73	0.81	0.82	....
N6791*2038	....	gK	0.05	1.15	0.86	....	....	....	....	....
N6791*2045	....	gK	0.05	0.99	0.92	....	0.72	0.82	0.83	....

Star	B-V	ST	[Fe/H]	Mg	H β	Fe46	Fe49	Fe50	Fe52	Fe53
N6791*152.3	....	gK	0.05	0.87	0.93	....	0.76	0.81	0.81	....
N6791*152.4	....	gK	0.05	0.97	0.90	....	0.74	0.80	0.83	....
N6791*152.5	....	gK	0.05	0.93	0.89	....	0.78	0.80	0.84	....
M71*I113	1.03	gK	-0.58	0.84	1.09	0.90	0.88	0.83	0.81	0.91
M71* _s 232	1.18	gM	-0.58	0.72	0.87	1.11	0.67	0.70	0.76	0.87
M4*2519	1.06	gK	-1.05	0.85	0.83	0.75	0.77	0.81	0.82	0.88
M4*1411	1.35	gK	-1.05	0.95	0.82	0.79	0.73	0.79	0.81	0.87
M4*2406	1.29	gK	-1.05	0.85	0.86	0.78	0.75	0.82	0.82	0.86
M4*2307	1.32	gK	-1.05	0.92	0.86	0.82	0.76	0.79	0.83	0.86
M4*3612	1.07	gK	-1.05	0.93	0.83	0.81	0.76	0.81	0.82	0.85
M4*1408	1.01	gK	-1.05	0.89	0.81	0.81	0.82	0.81	0.83	0.86
M4*1501	1.13	gK	-1.05	0.90	0.84	0.80	0.77	0.78	0.87	0.89
M4*4201	0.98	gK	-1.05	0.83	0.84	0.80	0.78	0.82	0.80	0.84
M4*4511	1.19	gK	-1.05	0.92	0.81	0.81	0.76	0.79	0.83	0.89
M4*3209	1.26	gK	-1.05	0.90	0.86	0.85	0.72	0.79	0.85	0.88
M4*4414	0.93	gK	-1.05	0.81	0.81	0.79	0.78	0.81	0.80	0.85
M4*2617	1.20	gK	-1.05	0.89	0.80	0.83	0.76	0.81	0.82	0.87
M4*3413	1.12	gK	-1.05	0.82	0.83	0.83	0.70	0.80	0.84	0.85
M3*192	1.00	gK	-1.66	0.75	0.84	0.83	0.75	0.76	0.76	0.85
M3*177	1.13	gK	-1.66	0.76	0.87	0.84	0.76	0.77	0.77	0.88
M3*837	1.50	gK	-1.66	0.85	0.86	0.84	0.77	0.79	0.81	0.87
M3*1392	1.37	gK	-1.66	0.78	0.86	0.83	0.80	0.80	0.77	0.84
M3*281	1.08	gK	-1.66	0.79	0.85	0.83	0.77	0.77	0.80	0.84
M3*1397	1.56	gK	-1.66	0.79	0.85	0.83	0.77	0.80	0.77	0.88
M3*194	0.98	gK	-1.66	0.79	0.80	0.79	0.79	0.78	0.77	0.86
M3*297	1.42	gK	-1.66	0.75	0.86	0.79	0.74	0.78	0.77	0.86
M3*398	1.15	gK	-1.66	0.81	0.82	0.82	0.79	0.79	0.83	0.86
M3*1362	1.04	gK	-1.66	0.77	0.82	0.81	0.78	0.78	0.80	0.83
M3*1127	1.23	gK	-1.66	0.74	0.85	0.79	0.77	0.81	0.76	0.84
M3*1270	0.94	gK	-1.66	0.74	0.84	0.79	0.79	0.79	0.80	0.84
M3*1345	1.05	gK	-1.66	0.76	0.84	0.73	0.83	0.75	0.82	0.85
M3*164	1.10	gK	-1.66	0.78	0.80	0.80	0.77	0.82	0.83	0.87
M3*115	1.29	gK	-1.66	0.79	0.77	0.63	0.67	....	0.70	0.80
M3*1376	1.16	gK	-1.66	0.77	0.81	0.77	0.89	0.81	0.88	....
M3*205	1.37	gK	-1.66	0.79	0.90	0.75	0.76	0.76	0.82	0.81
M3*853	0.88	gK	-1.66	0.73	0.89	0.85	0.81	0.79	0.75	0.85
N6402*O	....	gK	-1.39	0.85	0.90	....	0.65	0.81	0.80	....
N6402*K	....	gK	-1.39	0.89	0.97	....	0.53	0.84	0.78	....
N6402*A	....	gK	-1.39	0.77	0.69	....	0.66	0.78	0.80	....
N6366IV50	1.53	gK	-0.13	0.98	0.94	....	0.55	0.83	0.79	....
N6366*III8	1.18	gK	-0.13	....	....	0.70	....	0.80	....	....
N6366*I73	1.40	gK	-0.13	....	....	0.74	....	0.76	....	....

Table 2.9 : Spectral Indices

Star	Mg	H β	Fe492	Fe498	Fe50	Fe52	Fe53	Fe54	Mg1	Mg2	Mgb	MgH
NGC2141												
5003	1.15	0.71	0.65	0.98	0.88	0.93	0.89	0.76	1.15	1.38	0.89	0.95
4019	1.16	0.72	0.63	0.96	0.86	0.93	0.91	0.81	1.15	1.40	0.85	0.95
5013	1.19	0.65	0.70	1.08	0.92	0.95	0.88	0.83	1.18	1.43	0.81	0.99
4032	0.98	0.77	0.76	0.90	0.89	0.91	0.78	0.67	0.96	1.06	0.85	0.77
4025	1.10	0.75	0.68	0.91	0.80	0.92	0.91	0.82	1.02	1.29	0.96	0.84
3274	0.91	0.75	0.68	0.88	0.81	0.90	0.85	0.80	0.86	1.04	0.99	0.69
2142	0.92	0.85	0.74	0.94	0.89	0.85	0.78	0.79	0.88	1.07	0.83	0.68
2444	0.88	0.86	0.62	0.86	0.79	0.86	0.88	0.80	0.83	1.05	0.90	0.66
3253	0.91	0.73	0.64	0.91	0.78	0.88	0.85	0.79	0.84	1.08	0.90	0.71
2329	0.95	0.76	0.69	0.93	0.82	0.88	0.83	0.82	0.85	1.08	0.93	0.71
2210	1.48	1.02	1.17	1.60	1.93	0.96	0.85	0.76	1.36	1.81	1.02	1.02
3436	0.92	0.81	0.69	0.91	0.83	0.88	0.84	0.75	0.92	1.08	0.90	0.64
3234	0.90	0.78	0.64	1.06	0.83	0.90	0.84	0.79	0.78	1.05	0.88	0.64
3116	0.91	0.80	0.66	0.93	0.86	0.90	0.89	0.81	0.91	1.10	0.79	0.69
3429	1.00	1.27	0.72	0.96	0.88	0.96	0.91	0.76	0.86	1.27	0.83	0.79
NGC2158												
4269	1.14	0.73	0.64	0.97	0.88	0.93	0.93	0.81	1.08	1.34	0.96	1.01
1116	1.00	0.75	0.67	0.92	0.84	0.91	0.89	0.82	1.00	1.17	0.82	0.81
3132	1.03	0.75	0.68	0.94	0.85	0.90	0.87	0.82	1.02	1.22	0.95	0.82
2316	1.28	0.75	0.57	0.98	0.83	0.99	0.91	0.82	1.17	1.62	0.95	0.96
4512	1.05	0.70	0.75	0.83	0.82	1.02	0.79	0.68	1.04	1.14	0.88	0.92
24c	0.90	0.75	0.69	0.88	0.84	0.91	0.89	0.81	0.91	1.01	0.80	0.73
2287	0.93	0.72	0.63	0.92	0.79	0.90	0.86	0.80	0.86	1.12	0.91	0.75
3401	0.96	0.68	0.60	0.97	0.80	0.93	0.87	0.81	0.88	1.10	0.94	0.72
3415	1.10	0.71	0.59	0.95	0.85	0.91	0.89	0.81	1.07	1.35	0.83	0.79
2416	0.97	0.83	0.63	0.95	0.82	0.89	0.87	0.76	0.95	1.17	0.81	0.79
1325	0.82	0.77	0.64	0.85	0.77	0.88	0.86	0.79	0.76	0.95	0.90	0.60
1502	0.95	0.77	0.71	0.95	0.83	0.87	0.86	0.76	0.92	1.17	0.81	0.73
1515	0.81	0.79	0.69	0.94	0.82	0.84	0.83	0.80	0.74	0.94	0.87	0.59
4508	0.81	0.70	0.70	0.93	0.87	0.86	0.86	0.80	0.79	0.96	0.72	0.69
4413	0.84	0.70	0.68	0.93	0.87	0.87	0.86	0.78	0.78	0.98	0.93	0.60
1310	0.98	0.89	0.75	1.05	0.89	0.89	0.71	0.66	0.93	1.16	0.82	0.71
4320	0.83	0.81	0.66	0.84	0.76	0.86	0.88	0.79	0.76	1.02	0.85	0.65
2520	0.88	0.79	0.70	0.95	0.84	0.90	0.82	0.75	0.86	1.10	0.78	0.67
3413	0.91	0.75	0.67	0.94	0.84	0.88	0.85	0.81	0.89	1.14	0.90	0.72
4401	0.89	0.76	0.70	0.97	0.81	0.94	0.88	0.78	0.83	1.07	0.90	0.67
NGC2204												
4132	0.98	0.82	0.23	1.41	1.19	0.76	0.73	0.61	1.20	0.96	1.36	1.28
2120	0.96	0.74	0.68	0.89	0.84	0.91	0.90	0.83	0.97	1.07	0.94	0.84
4137	1.04	0.87	0.65	0.86	0.85	0.88	0.83	0.82	1.04	1.13	0.89	0.88
4212	0.91	0.76	0.69	1.02	0.81	0.87	0.87	0.80	0.83	0.94	0.92	0.66
1320	0.89	0.91	0.70	0.91	0.83	0.86	0.81	0.84	0.87	0.94	0.82	0.84
3207	0.93	0.85	0.73	0.90	0.82	0.79	0.85	0.78	0.84	0.95	0.80	0.65
1136	0.92	0.82	0.24	1.91	1.40	0.96	0.87	0.68	1.18	0.94	1.21	1.43
1129	0.91	0.89	0.68	0.88	0.85	0.87	0.80	0.83	0.90	0.94	0.85	0.87
2212	0.93	0.79	0.73	0.94	0.85	0.88	0.79	0.82	0.89	1.03	0.83	0.73
2136	0.85	0.85	0.67	0.91	0.85	0.86	0.77	0.79	0.84	0.96	0.85	0.67
3145	0.85	0.66	0.65	0.91	0.78	0.92	0.89	0.79	0.76	0.91	0.91	0.61
3215	0.82	0.91	0.70	0.97	0.79	0.80	0.80	0.80	0.82	0.90	0.81	0.73

Star	Mg	H β	Fe492	Fe498	Fe50	Fe52	Fe53	Fe54	Mg1	Mg2	Mgb	MgH
4216	0.87	0.88	0.68	1.02	0.88	0.82	0.77	0.76	0.82	0.92	0.85	0.62
1133	0.87	0.84	0.78	0.82	0.85	0.82	0.78	0.82	0.83	0.91	0.83	0.70
4210	0.93	0.75	0.76	0.91	0.76	0.93	0.87	0.85	0.94	1.01	1.04	0.69
2229	0.84	0.88	0.73	0.86	0.81	0.86	0.77	0.79	0.78	0.95	0.79	0.85
1212	0.86	0.95	0.72	0.89	0.84	0.74	0.85	0.81	0.85	0.94	0.88	0.75
3205	0.90	0.76	0.74	0.89	0.84	0.85	0.74	0.77	0.87	0.93	0.79	0.65
4116	0.84	0.69	0.66	0.89	0.84	0.90	0.91	0.83	0.83	0.97	0.77	0.65
4123	0.91	1.01	0.68	0.83	0.76	0.84	0.75	0.84	0.94	0.93	0.90	0.96
NGC2243												
2141	0.85	0.82	0.69	0.83	0.76	0.79	0.80	0.81	0.76	0.92	0.75	0.64
3312	1.03	0.90	0.70	0.94	0.85	0.86	0.79	0.79	1.04	1.16	0.94	0.78
3128	1.03	0.73	0.69	0.95	0.79	0.83	0.82	0.81	0.97	1.07	1.05	0.75
4303	0.86	0.88	0.68	0.86	0.79	0.79	0.86	0.80	0.83	1.00	0.71	0.84
4137	0.88	0.90	0.70	0.96	0.82	0.83	0.73	0.79	0.84	1.02	0.81	0.61
2308	0.85	0.89	0.65	0.93	0.84	0.82	0.77	0.81	0.81	1.02	0.82	0.61
2245	0.90	0.89	0.66	0.96	0.83	0.82	0.76	0.80	0.85	1.08	0.80	0.79
3110	0.91	0.88	0.67	0.98	0.86	0.82	0.78	0.79	0.87	1.09	0.81	0.67
3316	0.86	0.90	0.66	0.88	0.82	0.84	0.86	0.80	0.84	0.97	0.83	0.81
2314	0.91	0.87	0.68	1.00	0.89	0.81	0.76	0.80	0.85	1.07	0.80	0.64
1219	1.04	0.87	0.69	0.92	0.81	0.85	0.88	0.81	0.94	1.17	0.80	0.77
4110	0.91	0.91	0.65	0.93	0.80	0.80	0.88	0.80	0.89	1.11	0.74	0.85
4209	1.18	0.75	0.66	1.07	0.83	0.88	0.80	0.81	1.16	1.45	0.85	0.90
NGC2477												
es399	1.10	0.74	0.55	0.90	0.82	0.94	0.94	0.79	1.11	1.19	1.02	1.10
h2117	1.15	0.70	0.60	0.94	0.84	0.90	0.94	0.79	1.12	1.21	1.01	1.09
es602	0.99	0.78	0.72	0.91	0.83	0.85	0.88	0.82	0.91	1.03	0.81	0.79
es785	1.00	0.74	0.71	0.89	0.81	0.83	0.91	0.83	0.92	1.06	0.80	0.79
es920	1.00	0.72	0.72	0.88	0.81	0.84	0.90	0.83	0.91	1.07	0.81	0.81
es956	0.95	0.75	0.71	0.88	0.81	0.84	0.89	0.83	0.85	1.01	0.80	0.73
es915	0.96	0.83	0.70	0.90	0.81	0.83	0.88	0.84	0.88	1.04	0.78	0.75
es879	1.13	0.79	0.56	1.01	0.94	0.92	0.82	0.81	1.20	1.21	0.94	1.10
es752	0.91	0.71	0.66	0.86	0.79	0.90	0.89	0.83	0.86	1.01	0.92	0.69
es270	0.86	0.86	0.63	0.87	0.79	0.90	0.88	0.81	0.80	0.99	0.90	0.66
es430	0.90	0.80	0.71	0.91	0.81	0.83	0.88	0.84	0.80	0.98	0.77	0.66
es396	0.93	0.78	0.70	0.88	0.80	0.83	0.89	0.83	0.83	0.99	0.76	0.70
es902	0.85	0.78	0.66	0.86	0.79	0.91	0.83	0.81	0.80	0.96	0.88	0.68
es911	0.86	0.88	0.66	0.88	0.80	0.82	0.86	0.81	0.84	0.97	0.77	0.81
es272	0.92	0.74	0.71	0.90	0.80	0.89	0.80	0.81	0.83	0.99	0.91	0.66
es959	0.86	0.89	0.71	0.94	0.83	0.86	0.76	0.83	0.85	0.91	0.85	0.87
es696	0.89	0.74	0.70	0.91	0.81	0.86	0.86	0.82	0.81	0.95	0.93	0.69
es913	0.89	0.86	0.69	0.92	0.80	0.80	0.86	0.81	0.80	0.96	0.77	0.63
NGC2506												
3254	1.08	0.79	0.65	0.90	0.80	0.85	0.90	0.82	0.99	1.22	0.79	0.83
2122	0.89	0.88	0.68	0.90	0.81	0.81	0.88	0.81	0.87	1.03	0.83	0.84
2212	0.90	0.90	0.69	0.96	0.84	0.84	0.88	0.81	0.86	1.04	0.82	0.84
3204	0.83	0.89	0.68	0.89	0.80	0.79	0.86	0.80	0.81	0.97	0.74	0.78
1112	0.90	0.84	0.68	0.93	0.82	0.81	0.85	0.81	0.87	1.07	0.84	0.83
2364	0.85	0.93	0.68	0.93	0.83	0.82	0.77	0.80	0.81	0.96	0.79	0.81
4376	0.88	0.86	0.66	0.91	0.82	0.84	0.84	0.79	0.84	1.02	0.80	0.82
2309	0.92	0.89	0.66	0.96	0.88	0.83	0.78	0.79	0.87	1.09	0.83	0.66
3231	0.87	0.89	0.68	0.88	0.80	0.79	0.86	0.80	0.82	1.00	0.74	0.63

Star	Mg	H β	Fe492	Fe498	Fe50	Fe52	Fe53	Fe54	Mg1	Mg2	Mgb	MgH
4240	0.83	0.90	0.67	0.92	0.79	0.76	0.86	0.80	0.81	0.97	0.71	0.80
1325	0.88	0.89	0.70	0.95	0.83	0.83	0.78	0.80	0.84	1.03	0.81	0.82
2480	0.89	0.90	0.66	0.95	0.84	0.84	0.85	0.79	0.86	1.01	0.82	0.82
23101	0.89	0.87	0.66	0.94	0.87	0.84	0.79	0.81	0.85	1.04	0.79	0.65
3265	0.89	0.90	0.69	0.86	0.79	0.82	0.75	0.80	0.85	1.01	0.80	0.79
3324	0.84	0.88	0.68	0.90	0.82	0.83	0.85	0.82	0.82	0.95	0.83	0.78
3359	0.92	0.88	0.65	0.87	0.79	0.81	0.85	0.79	0.87	1.06	0.74	0.66
4109	0.94	0.77	0.66	0.90	0.77	0.80	0.86	0.84	0.85	1.08	0.80	0.66
4274	0.89	0.85	0.67	0.88	0.79	0.79	0.87	0.81	0.80	1.02	0.77	0.63
3271	0.82	0.89	0.66	0.88	0.81	0.82	0.77	0.79	0.80	0.91	0.79	0.82
1301	0.88	0.90	0.70	0.92	0.85	0.79	0.85	0.80	0.85	0.99	0.81	0.85
47Tuc												
W3	1.09	0.81	0.60	0.87	0.81	0.83	0.91	0.81	1.09	1.22	0.88	1.18
3086	1.09	0.67	0.61	1.02	0.80	0.87	0.90	0.79	1.04	1.15	1.01	0.94
3027	1.06	0.79	0.64	0.90	0.79	0.81	0.90	0.80	0.98	1.16	0.83	0.94
W280	1.00	0.74	0.66	0.87	0.79	0.80	0.86	0.80	1.00	1.13	0.81	1.07
4004	1.04	0.78	0.65	0.89	0.80	0.76	0.89	0.82	1.04	1.13	0.87	1.10
1031	1.11	0.71	0.65	0.87	0.80	0.82	0.87	0.79	1.01	1.18	0.85	0.92
3023	0.96	0.85	0.70	0.89	0.80	0.77	0.88	0.80	0.94	1.07	0.87	1.02
LE346	1.00	0.82	0.67	0.90	0.83	0.83	0.76	0.82	0.99	1.09	0.88	1.01
N1108	1.31	0.15	0.75	1.72	1.20	0.50	0.48	0.41	1.80	0.94	1.91	1.23
LE343	0.95	0.85	0.69	0.93	0.83	0.82	0.87	0.80	0.94	1.07	0.87	0.97
LE354	0.97	0.18	0.60	0.84	0.83	0.76	0.68	0.76	0.90	1.22	0.84	0.91
W92	0.93	0.80	0.72	0.94	0.80	0.75	0.85	0.80	0.96	0.98	0.97	0.88
3006	0.94	0.88	0.67	0.89	0.81	0.83	0.86	0.78	0.93	1.02	0.88	0.96
3016	0.71	-1.06	-0.11	-0.46	0.55	0.54	0.83	0.11	0.67	0.87	0.28	0.55
792	1.10	0.78	0.62	0.86	0.79	0.79	0.88	0.81	1.10	1.20	0.84	1.18
542	1.13	0.79	0.56	0.91	0.83	0.77	0.89	0.76	1.18	1.23	0.94	1.23
265	1.09	0.86	0.51	0.95	0.85	0.73	0.83	0.74	1.14	1.15	0.90	1.21
481	1.05	0.89	0.63	0.93	0.83	0.80	0.88	0.81	1.08	1.07	0.92	1.15
343	1.14	0.89	0.45	1.07	0.95	0.80	0.87	0.70	1.26	1.17	1.05	1.37
426	1.11	0.81	0.50	0.97	0.85	0.79	0.88	0.75	1.18	1.20	1.00	1.26
525	1.11	0.76	0.62	0.88	0.80	0.80	0.89	0.79	1.04	1.12	0.88	0.95
870	1.06	0.86	0.64	0.91	0.82	0.83	0.88	0.80	1.05	1.16	0.87	1.13
410	1.12	0.86	0.44	1.07	0.93	0.81	0.86	0.70	1.23	1.15	1.07	1.25
559	1.10	0.83	0.62	0.92	0.83	0.83	0.78	0.79	1.09	1.17	0.90	1.16
342	1.04	0.86	0.67	0.89	0.82	0.83	0.87	0.80	1.03	1.09	0.88	1.10
431	1.10	0.79	0.69	0.88	0.83	0.82	0.84	0.84	1.03	1.16	0.85	1.12
484	1.06	0.74	0.69	0.86	0.79	0.79	0.88	0.82	1.04	1.11	0.84	0.90
390	1.06	0.86	0.67	0.91	0.82	0.83	0.90	0.82	1.05	1.17	0.89	1.11
355	1.02	0.85	0.68	0.92	0.84	0.84	0.78	0.82	1.01	1.10	0.89	0.84
341	0.98	0.79	0.71	0.91	0.81	0.82	0.88	0.79	0.92	1.00	0.80	0.75
55	1.03	0.88	0.70	0.89	0.82	0.81	0.88	0.80	0.97	1.05	0.89	0.99
523	0.98	0.88	0.67	0.92	0.83	0.83	0.77	0.81	0.95	1.06	0.88	0.98
769	0.99	0.69	0.64	0.87	0.79	0.84	0.85	0.80	0.91	1.07	0.93	0.83
573	0.99	0.77	0.68	0.87	0.82	0.79	0.88	0.84	0.91	1.04	0.87	0.77
907	0.96	0.86	0.68	0.92	0.83	0.82	0.77	0.79	0.94	1.01	0.86	0.77
371	1.00	0.87	0.66	0.96	0.83	0.82	0.79	0.80	0.99	1.08	0.87	1.02
514	0.94	0.85	0.67	0.90	0.83	0.82	0.77	0.82	0.95	0.97	0.86	0.98
863	0.94	0.80	0.69	0.85	0.78	0.80	0.84	0.80	0.86	1.02	0.78	0.75
cfxen	0.93	0.79	0.69	0.74	0.82	0.86	0.85	0.84	0.87	1.01	0.94	0.76

Star	Mg	H β	Fe492	Fe498	Fe50	Fe52	Fe53	Fe54	Mg1	Mg2	Mgb	MgH
458	0.89	0.93	0.69	0.95	0.84	0.83	0.76	0.80	0.86	1.02	0.83	0.63
624	1.05	0.85	0.65	0.89	0.82	0.86	0.89	0.80	1.04	1.14	0.89	0.99
191	1.18	0.68	0.60	1.05	0.81	0.87	0.90	0.80	1.10	1.34	0.98	0.97
637	1.06	0.70	0.66	0.91	0.80	0.81	0.88	0.82	0.97	1.18	0.82	0.85
4	1.11	0.80	0.66	0.90	0.80	0.81	0.86	0.80	1.01	1.24	0.82	0.88
6	0.82	0.83	0.67	0.87	0.78	0.76	0.82	0.78	0.73	0.92	0.74	0.61
680	1.05	0.88	0.21	1.35	1.14	0.77	0.77	0.61	1.22	1.06	1.26	1.19
195	0.97	0.82	0.67	0.90	0.80	0.78	0.84	0.80	0.87	1.11	0.77	0.72
NGC1851												
336	0.75	0.79	0.56	0.66	0.63	0.67	0.86	0.89	0.66	0.92	0.74	0.65
249	0.85	0.57	0.81	0.89	0.82	0.77	0.68	0.80	0.80	0.86	0.78	0.56
399	0.77	0.52	0.57	0.76	0.58	0.81	0.91	0.83	0.75	0.98	0.75	0.73
136	0.95	0.93	0.66	0.73	0.76	0.84	0.73	0.85	0.86	0.78	0.68	0.70
41	0.80	0.52	0.38	1.83	0.82	0.74	0.74	0.76	0.71	0.80	0.74	0.70
319	0.87	0.77	0.68	0.77	0.78	0.90	0.88	0.79	0.76	0.93	0.77	0.83
126	0.92	0.69	0.69	0.91	0.80	0.86	0.79	0.76	0.84	0.99	0.93	0.58
107	0.87	0.81	0.73	0.77	0.79	0.75	0.86	0.81	0.81	0.95	0.72	0.84
333	0.86	0.78	0.64	0.88	0.84	0.75	0.69	0.74	0.84	0.98	0.75	0.69
279	0.89	0.71	0.65	0.80	0.80	0.81	0.79	0.80	0.81	0.97	0.83	0.66
151	0.92	0.82	0.68	0.83	0.81	0.77	0.79	0.76	0.81	0.97	0.72	0.67
3	0.87	0.79	0.66	0.83	0.79	0.76	0.79	0.77	0.84	0.95	0.75	0.83
112	1.00	0.64	0.65	0.80	0.81	0.73	0.71	0.73	0.89	1.02	0.80	0.70
262	0.96	0.75	0.63	0.76	0.76	0.81	0.76	0.74	0.92	1.03	0.82	0.77
395	0.99	0.93	0.66	0.77	0.76	0.86	0.78	0.79	0.90	1.02	0.82	0.72
294	1.04	0.72	0.69	0.81	0.79	0.83	0.77	0.75	0.91	1.07	0.78	0.76
329	1.07	0.86	0.66	0.78	0.78	0.79	0.79	0.76	0.98	1.09	0.76	0.79
168v	1.00	0.71	0.50	0.77	0.76	0.86	0.84	0.76	0.99	1.17	0.86	0.81
M4												
139	0.97	0.79	0.68	0.79	0.80	0.83	0.84	0.61	0.81	0.82	0.79	0.75
123	0.86	0.80	0.66	0.75	0.77	0.81	0.85	0.52	0.70	0.72	0.82	0.69
246	1.10	0.83	0.67	0.81	0.81	0.87	0.87	0.61	0.91	0.85	0.94	0.73
248	0.92	0.78	0.73	0.84	0.83	0.83	0.75	0.48	0.77	0.76	0.86	0.74
297	1.03	0.78	0.69	0.84	0.79	0.87	0.80	0.51	0.88	0.83	0.94	0.82
308	0.95	0.83	0.74	0.83	0.82	0.82	0.81	0.59	0.79	0.73	0.92	0.64
4611	1.08	0.77	0.62	0.85	0.79	0.78	0.79	0.49	0.91	0.95	0.90	0.82
4613	1.11	0.81	0.60	0.84	0.80	0.85	0.87	0.58	0.92	0.98	0.89	0.82
4624	0.93	0.76	0.75	0.74	0.79	0.79	0.75	0.51	0.82	0.69	0.81	0.82
4621	0.84	0.80	0.68	0.87	0.76	0.76	0.79	0.50	0.65	0.70	0.79	0.62
4602	0.88	0.82	0.70	0.77	0.77	0.75	0.73	0.40	0.71	0.76	0.79	0.66
4414	0.85	0.81	0.72	0.82	0.78	0.80	0.75	0.60	0.76	0.74	0.80	0.68
4415	0.86	0.81	0.72	0.82	0.78	0.80	0.75	0.60	0.78	0.74	0.83	0.68
NGC288												
096	0.95	0.75	0.72	0.90	0.84	0.84	0.84	0.75	0.94	1.06	0.85	0.79
078	0.94	0.77	0.70	0.90	0.85	0.83	0.84	0.75	0.92	1.06	0.83	0.76
213	0.92	0.74	0.71	0.93	0.84	0.84	0.84	0.75	0.90	1.04	0.82	0.75
219	0.81	0.88	0.68	0.90	0.83	0.83	0.75	0.78	0.78	0.92	0.80	0.64
186	0.84	0.74	0.70	0.90	0.81	0.83	0.83	0.77	0.83	0.96	0.75	0.68
231	0.87	0.89	0.68	0.89	0.83	0.83	0.75	0.82	0.85	0.99	0.83	0.71
307	0.83	0.89	0.69	0.90	0.81	0.80	0.75	0.80	0.81	0.91	0.82	0.66
277	0.88	0.88	0.67	0.91	0.83	0.83	0.71	0.64	0.86	1.00	0.78	0.74
007	0.82	0.73	0.69	0.89	0.82	0.82	0.82	0.78	0.81	0.96	0.86	0.66

Star	Mg	H β	Fe492	Fe498	Fe50	Fe52	Fe53	Fe54	Mg1	Mg2	Mgb	MgH
070	0.82	0.74	0.68	0.89	0.82	0.82	0.82	0.77	0.81	0.96	0.76	0.65
178	0.85	0.85	0.75	0.89	0.83	0.83	0.61	0.63	0.83	0.98	0.81	0.68
206	0.82	0.68	0.65	0.86	0.78	0.81	0.83	0.77	0.73	0.93	0.84	0.64
131	0.81	0.72	0.69	0.92	0.83	0.83	0.80	0.75	0.79	0.92	0.77	0.63
019	0.83	0.74	0.71	0.92	0.83	0.83	0.83	0.73	0.80	0.96	0.80	0.63
027	0.83	0.74	0.66	0.87	0.79	0.72	0.81	0.79	0.74	0.88	0.69	0.64
NGC362												
2124	0.81	0.91	0.65	0.89	0.85	0.76	0.81	0.80	0.76	0.99	0.73	0.62
2212	0.92	0.80	0.64	0.86	0.79	0.91	0.83	0.79	0.82	1.06	0.87	0.66
2401	0.93	0.82	0.68	0.92	0.81	0.87	0.87	0.81	0.82	1.08	0.88	0.67
2309	0.92	0.88	0.65	0.92	0.81	0.80	0.84	0.78	0.82	1.05	0.73	0.65
2223	0.82	0.76	0.67	0.87	0.83	0.81	0.75	0.80	0.80	0.96	0.80	0.61
pe55	0.83	0.75	0.63	0.85	0.77	0.86	0.85	0.82	0.78	0.99	0.90	0.62
pe63	0.89	0.88	0.68	0.92	0.84	0.77	0.86	0.81	0.87	1.00	0.83	0.81
pe45	0.89	0.69	0.63	0.80	0.74	0.84	0.84	0.80	0.82	1.05	0.87	0.64
2302	0.92	0.71	0.65	0.89	0.80	0.92	0.88	0.81	0.81	1.05	0.85	0.66
2108	0.91	0.71	0.66	1.01	0.79	0.87	0.83	0.79	0.80	1.06	0.85	0.66
2113	0.94	0.73	0.69	0.93	0.82	0.87	0.64	0.69	0.92	1.10	0.87	0.69
pe65	0.94	0.70	0.67	0.91	0.81	0.91	0.84	0.80	0.83	1.07	0.90	0.66
2213	0.86	0.76	0.68	0.87	0.83	0.85	0.75	0.82	0.84	1.02	0.79	0.64
2423	0.98	0.68	0.63	1.02	0.79	0.86	0.82	0.78	0.89	1.12	0.85	0.74
1441	0.90	0.75	0.65	0.89	0.83	0.85	0.74	0.65	0.87	1.09	0.74	0.67
2115	0.83	0.77	0.62	0.88	0.77	0.80	0.85	0.76	0.81	0.97	0.85	0.62
cent	0.85	0.92	0.67	0.92	0.85	0.82	0.77	0.80	0.81	0.96	0.79	0.64
NGC6356												
000	1.05	0.82	0.52	0.89	0.82	0.85	0.87	0.64	1.04	0.92	0.97	1.00
115	0.96	0.82	0.27	1.25	1.06	0.87	0.79	0.51	1.11	0.81	1.13	1.06
000	0.90	0.87	0.68	0.67	0.75	0.81	0.75	0.56	0.70	0.74	0.77	0.49
113	0.98	0.88	0.66	0.89	0.79	0.89	0.87	0.65	0.89	0.85	0.92	0.78
111	1.05	0.77	0.59	0.79	0.79	0.85	0.78	0.52	0.99	0.97	0.91	1.03
000	0.99	0.79	0.67	0.86	0.82	0.87	0.85	0.65	0.89	0.87	0.88	0.81
104	1.00	0.76	0.69	0.79	0.79	0.87	0.83	0.62	0.95	0.84	0.83	0.87
000	0.89	0.91	0.66	0.91	0.82	0.87	0.82	0.60	0.78	0.78	0.90	0.72
162	0.75	0.81	0.65	0.79	0.74	0.73	0.70	0.54	0.63	0.70	0.78	0.55
000	0.82	0.79	0.76	0.77	0.77	0.82	0.82	0.72	0.71	0.71	0.85	0.74
000	0.82	0.81	0.78	0.90	0.81	0.88	0.78	0.58	0.75	0.78	0.92	0.67
000	0.88	0.75	0.70	0.85	0.83	0.88	0.88	0.61	0.75	0.71	0.93	0.67
37	1.04	0.84	0.25	1.06	1.03	0.80	0.77	0.54	1.15	0.89	1.17	1.13
000	0.80	0.79	0.64	0.78	0.79	0.78	0.75	0.45	0.65	0.71	0.78	0.64
80	1.14	0.76	0.52	0.91	0.85	0.87	0.88	0.62	1.13	1.07	0.93	1.08
NGC6440												
a	1.03	0.88	0.31	1.12	0.91	0.86	0.76	0.39	1.01	1.02	0.85	1.12
c	0.98	0.89	-0.01	0.97	0.93	0.93	0.77	0.39	1.20	0.85	1.42	1.23
y	0.81	0.76	0.59	0.85	0.72	0.80	0.77	0.47	0.67	0.75	0.90	0.56
b	1.02	0.60	0.63	0.85	0.87	0.86	0.92	0.47	1.05	0.99	1.24	1.00
x	0.92	1.19	0.39	0.75	0.71	0.93	0.63	0.50	0.87	0.99	0.78	0.96
1	0.98	0.74	0.58	1.02	0.83	0.80	0.79	0.32	0.91	0.92	0.89	0.87
ce	0.97	0.85	0.59	0.88	0.82	0.78	0.73	0.36	0.87	0.85	0.88	0.73
3	0.89	0.79	0.54	0.90	0.83	0.81	0.83	0.45	0.77	0.81	0.89	0.67
f	0.94	0.46	0.27	1.23	1.01	0.83	0.75	0.42	1.11	0.92	1.20	1.14
e	1.00	0.88	0.57	1.03	1.05	1.01	0.76	0.41	1.24	0.83	1.50	0.86

Star	Mg	H β	Fe492	Fe498	Fe50	Fe52	Fe53	Fe54	Mg1	Mg2	Mgb	MgH
d	1.15	0.72	0.43	0.92	0.77	0.86	0.86	0.45	1.10	1.11	1.29	1.13
NGC6528												
000	0.83	0.91	0.75	0.81	0.76	0.79	0.81	0.62	0.71	0.69	0.81	0.63
I-7	1.00	0.77	0.59	0.89	0.85	0.84	0.87	0.52	0.98	0.88	0.92	0.94
000	0.88	0.63	0.76	0.69	0.76	0.83	0.83	0.42	0.77	0.78	0.90	0.64
I-6	1.00	0.80	0.68	0.81	0.80	0.79	0.85	0.54	0.91	0.92	0.84	0.80
000	1.00	0.77	0.66	0.84	0.84	0.84	0.83	0.49	0.90	0.85	0.93	0.71
I-8	0.97	0.76	0.57	0.89	0.86	0.82	0.81	0.50	0.98	0.87	0.93	0.91
000	1.06	0.95	0.65	0.60	0.85	0.83	0.88	0.94	0.94	0.91	0.92	1.10
000	0.87	0.78	0.64	0.89	0.81	0.83	0.80	0.54	0.73	0.80	0.80	0.64
000	0.99	0.83	0.64	0.85	0.83	0.85	0.89	0.50	0.90	0.87	0.90	0.77
000	0.98	0.79	0.59	0.87	0.88	0.85	0.86	0.33	0.95	0.78	0.93	0.92
000	0.94	0.80	0.55	0.73	0.82	0.77	0.87	0.68	0.90	0.79	0.95	0.91
NGC6553												
II-5	1.17	0.73	0.60	0.77	0.84	0.91	0.78	0.72	1.17	1.11	0.94	0.99
000	0.97	0.80	0.67	0.88	0.83	0.86	0.90	0.80	0.93	0.93	0.89	0.87
III-4	1.03	0.82	0.59	0.81	0.84	0.92	0.88	0.87	1.01	1.04	0.96	0.98
000	0.96	0.72	0.66	0.92	0.81	0.94	0.76	0.73	0.95	0.93	1.02	0.80
III-15	0.93	0.80	0.70	0.86	0.81	0.91	0.80	0.89	0.87	0.87	0.93	0.78
III-10	0.67	0.90	0.64	0.92	0.85	0.81	0.82	0.75	0.62	0.74	0.95	0.51
000	0.96	0.82	0.59	0.79	0.84	0.91	0.85	0.84	1.00	0.91	0.96	0.97
000	0.96	0.87	0.72	0.80	0.79	0.84	0.72	1.02	0.90	0.93	0.95	0.71
NGC6624												
I102	0.95	0.70	0.68	1.06	0.83	0.80	0.87	0.81	0.81	1.11	0.86	0.73
0000	0.88	0.79	0.72	0.94	0.85	0.84	0.62	0.63	0.85	1.03	0.80	0.67
0000	0.93	0.74	0.68	0.84	0.79	0.85	0.85	0.79	0.88	1.14	0.98	0.69
I130	0.81	0.78	0.68	0.90	0.81	0.82	0.83	0.73	0.79	0.99	0.79	0.64
U	0.96	0.95	0.19	1.56	1.29	0.80	0.77	0.59	1.18	0.98	1.35	1.32
I40	0.83	1.26	0.58	1.07	0.85	0.86	0.64	0.69	0.87	0.82	0.92	0.48
I43	0.84	0.79	0.64	0.89	0.78	0.74	0.82	0.76	0.73	1.00	0.70	0.58
0000	1.09	0.78	0.72	0.87	0.79	0.85	0.91	0.85	1.12	1.16	0.92	1.10
h	0.98	0.75	0.68	0.90	0.84	0.88	0.88	0.81	0.93	1.13	0.97	0.75
II28	0.86	0.80	0.70	0.85	0.81	0.86	0.77	0.84	0.83	1.03	0.79	0.65
III132	1.17	0.83	0.61	1.02	0.92	0.93	0.86	0.81	1.23	1.29	0.94	1.09
0000	1.16	0.88	0.43	1.05	0.95	0.85	0.77	0.70	1.26	1.26	1.05	1.09
e	0.92	0.75	0.69	0.88	0.79	0.86	0.83	0.80	0.87	1.09	0.93	0.71
K	1.02	0.88	0.72	0.91	0.86	0.89	0.80	0.80	1.00	1.16	0.86	0.80
III7	1.04	0.85	0.67	0.91	0.85	0.86	0.80	0.82	1.03	1.14	0.89	0.80
III12	0.99	0.71	0.66	0.86	0.75	0.86	0.83	0.79	0.94	1.15	0.96	0.75
III125	0.95	0.74	0.71	0.94	0.86	0.84	0.85	0.79	0.93	1.13	0.85	0.72
0000	0.97	0.82	0.65	0.95	0.87	0.83	0.77	0.79	0.94	1.13	0.82	0.77
III31	1.05	0.75	0.72	0.93	0.86	0.89	0.87	0.84	1.00	1.18	0.94	0.76
0000	1.22	0.89	0.61	0.93	0.83	0.85	0.96	0.82	1.22	1.33	0.86	1.01
0000	0.96	0.76	0.66	0.88	0.79	0.90	0.89	0.81	0.91	1.11	0.94	0.72
0000	0.82	0.77	0.65	0.98	0.88	0.81	0.74	0.80	0.78	0.99	0.74	0.67
A	0.91	0.75	0.66	1.07	0.81	0.85	0.86	0.80	0.81	1.03	0.90	0.66
0000	0.85	0.75	0.67	0.86	0.81	0.87	0.83	0.76	0.83	1.02	0.74	0.64
IV122	0.82	0.86	0.65	0.88	0.78	0.85	0.84	0.80	0.75	0.98	0.87	0.62
0000	1.14	0.92	0.48	1.03	0.93	0.89	0.82	0.75	1.22	1.24	0.97	1.21
IV155	0.83	0.74	0.63	0.82	0.75	0.85	0.85	0.78	0.76	1.01	0.85	0.64
0000	1.19	0.86	0.76	0.88	0.90	0.82	0.93	0.83	1.17	1.25	0.97	0.92

Star	Mg	H β	Fe492	Fe498	Fe50	Fe52	Fe53	Fe54	Mg1	Mg2	Mgb	MgH
0000	0.80	0.83	0.69	0.89	0.81	0.83	0.81	0.77	0.79	0.96	0.75	0.63
0000	1.04	0.76	0.69	0.88	0.84	0.93	0.91	0.83	1.05	1.16	0.85	0.87
0000	1.03	0.88	0.69	0.89	0.85	0.86	0.80	0.82	1.02	1.15	0.90	0.80
0000	1.24	0.64	0.63	1.08	0.82	0.82	0.90	0.82	1.17	1.36	0.98	1.09
0000	1.37	0.91	0.63	0.88	0.86	0.98	0.88	0.85	1.40	1.49	1.07	1.11
0000	1.45	0.69	0.61	0.90	0.83	0.91	0.96	0.81	1.40	1.63	0.89	1.37
0000	1.16	0.86	0.66	0.94	0.86	0.84	0.61	0.65	1.16	1.30	0.87	0.91
0000	1.05	0.75	0.77	0.84	0.79	0.85	0.89	0.79	0.95	1.11	0.75	0.68
0000	0.94	0.86	0.63	0.93	0.84	0.85	0.85	0.82	0.93	1.01	0.86	0.89
0000	1.14	0.87	0.62	0.96	0.88	0.84	0.81	0.80	1.16	1.25	0.94	0.98
0000	1.16	0.78	0.43	1.14	1.00	0.92	0.90	0.68	1.30	1.27	1.03	1.19
0000	0.93	0.88	0.71	0.95	0.87	0.87	0.76	0.79	0.90	1.09	0.81	0.72
0000	0.91	0.69	0.55	1.07	0.74	0.96	0.85	0.87	0.94	1.42	0.98	0.65
0000	0.86	0.88	0.70	0.91	0.85	0.81	0.76	0.79	0.86	0.94	0.91	0.65
NGC6637												
00000	0.89	1.02	0.67	0.89	0.80	0.74	0.86	0.83	0.83	1.00	0.70	0.62
III10	0.93	0.73	0.67	0.84	0.82	0.87	0.86	0.80	0.94	1.03	0.82	0.74
00000	1.06	0.81	0.62	0.93	0.88	0.89	0.80	0.82	1.10	1.13	0.91	0.91
III34	0.84	0.76	0.69	0.90	0.83	0.85	0.84	0.79	0.84	0.99	0.80	0.66
00000	1.16	0.80	0.62	0.89	0.88	0.81	0.85	0.81	1.20	1.24	0.97	1.05
III41	0.80	0.93	0.68	0.91	0.80	0.73	0.83	0.79	0.77	0.99	0.80	0.77
II41	0.82	0.76	0.67	0.82	0.80	0.86	0.76	0.74	0.81	0.99	0.77	0.66
00000	0.74	0.78	0.60	0.77	0.80	0.93	0.82	0.77	0.69	0.96	0.77	0.63
00000	0.89	0.78	0.63	0.92	0.81	0.88	0.84	0.80	0.82	1.04	0.91	0.65
II16	0.91	0.77	0.68	0.97	0.87	0.90	0.76	0.75	0.90	0.99	0.84	0.77
I43	0.70	0.42	0.24	1.93	1.31	0.84	0.95	0.66	1.06	0.90	1.19	1.35
I32	0.97	0.74	0.71	0.95	0.86	0.88	0.79	0.76	0.94	1.17	0.82	0.75
00000	1.19	0.72	0.64	0.92	0.83	0.86	0.93	0.82	1.13	1.28	0.88	1.06
00000	0.82	0.87	0.69	0.90	0.79	0.82	0.81	0.79	0.75	1.00	0.88	0.63
00000	0.95	0.90	0.70	0.89	0.81	0.86	0.79	0.83	0.94	1.01	0.91	0.91
00000	0.90	0.72	0.66	1.11	0.78	0.76	0.82	0.78	0.79	1.08	0.75	0.64
00000	0.88	0.76	0.62	1.01	0.79	0.79	0.78	0.82	0.79	0.96	0.84	0.69
19	0.84	1.05	0.67	0.87	0.84	0.86	0.79	0.86	0.88	0.98	0.93	0.72
II12	0.80	0.90	0.61	0.79	0.86	0.81	0.83	0.85	0.80	0.97	0.72	0.62
I8	0.93	0.84	0.68	0.85	0.84	0.78	0.83	0.83	0.91	1.10	0.86	0.82
00000	0.95	0.83	0.67	0.91	0.84	0.81	0.78	0.80	0.92	1.00	0.88	0.69
00000	0.89	0.71	0.64	0.87	0.80	0.81	0.85	0.81	0.79	1.02	0.89	0.69
II35	0.88	0.81	0.64	0.89	0.77	0.87	0.85	0.81	0.83	1.01	0.96	0.64
III2	0.86	0.49	0.68	0.77	0.84	0.83	0.83	0.82	0.71	0.97	0.70	0.59
M28												
RC461	0.79	0.79	0.55	0.81	0.79	0.80	0.84	0.48	0.72	0.70	0.83	0.70
a	0.92	0.80	0.59	0.82	0.80	0.85	0.87	0.57	0.81	0.79	0.88	0.70
b	1.10	0.79	0.51	0.84	0.81	0.89	0.90	0.56	1.01	0.97	0.97	0.94
000	0.61	1.20	0.59	0.91	0.83	0.74	0.79	0.57	0.44	0.60	0.77	0.55
000	1.05	0.85	0.64	0.89	0.78	0.95	0.91	0.48	1.01	0.83	1.04	0.86
d	1.12	0.75	0.47	0.85	0.81	0.87	0.90	0.57	1.08	1.00	0.92	0.92
c	1.00	0.79	0.67	0.84	0.81	0.80	0.82	0.37	0.93	0.80	0.76	0.73
000	1.03	0.80	0.57	0.69	0.78	0.82	0.88	0.66	1.01	0.87	0.95	0.88
000	0.91	0.77	0.58	0.70	0.83	0.77	0.84	0.51	0.78	0.72	0.80	0.65
000	1.16	0.58	0.74	0.67	0.71	0.81	0.75	0.34	1.08	0.83	0.52	1.52
000	0.97	0.95	0.62	0.65	0.70	0.92	0.98	0.52	0.90	0.78	1.03	0.70

Star	Mg	H β	Fe492	Fe498	Fe50	Fe52	Fe53	Fe54	Mg1	Mg2	Mgb	MgH
000	1.16	0.59	0.76	0.82	0.83	1.03	1.00	0.60	1.10	0.99	0.91	0.94
000	0.91	0.87	0.63	0.81	0.76	0.85	0.77	0.45	0.85	0.80	0.93	0.73
e	1.04	0.77	0.45	0.79	0.81	0.87	0.76	0.53	1.00	0.95	0.95	0.90
f	0.83	0.81	0.56	0.87	0.79	0.84	0.73	0.43	0.73	0.77	0.82	0.73
000	1.04	0.81	0.55	0.70	0.83	0.83	0.78	0.55	0.98	0.92	0.96	0.77
2-108	0.81	0.83	0.53	0.80	0.79	0.78	0.80	0.54	0.67	0.71	0.81	0.59
g	1.01	0.77	0.48	0.82	0.81	0.90	0.98	0.52	1.00	0.91	0.95	1.11
000	0.93	0.90	0.55	0.76	0.84	0.85	0.79	0.55	0.86	0.73	0.88	0.62
000	1.00	0.83	0.44	0.60	0.67	0.80	0.85	0.59	0.92	0.90	0.78	0.77
2-109	0.81	0.80	0.52	0.81	0.78	0.79	0.82	0.47	0.72	0.75	0.78	0.75
i	0.87	0.81	0.58	0.87	0.80	0.80	0.86	0.44	0.79	0.80	0.85	0.77
z'	0.76	0.91	0.57	0.80	0.77	0.74	0.70	0.42	0.67	0.68	0.79	0.62
000	0.96	0.95	0.54	0.79	0.80	0.84	0.88	0.42	0.93	0.83	0.86	0.86
000	0.79	0.89	0.55	0.74	0.79	0.75	0.71	0.42	0.70	0.68	0.84	0.57
k	1.08	0.79	0.39	0.85	0.87	0.84	0.89	0.52	1.08	0.99	0.93	1.22
l	1.09	0.77	0.54	0.85	0.83	0.86	0.88	0.55	1.00	0.97	0.95	0.92
000	0.87	1.03	0.57	0.69	0.78	0.84	0.83	0.48	0.79	0.76	0.89	0.64
000	0.83	0.91	0.52	0.80	0.81	0.76	0.84	0.60	0.73	0.69	0.83	0.64
n	1.04	0.83	0.51	0.82	0.84	0.86	0.88	0.58	0.94	0.91	0.83	0.79
m	1.06	0.75	0.55	0.87	0.82	0.85	0.87	0.49	0.95	0.99	0.91	0.89
000	0.99	0.87	0.60	0.72	0.80	0.87	0.80	0.50	0.90	0.75	0.85	0.88
000	1.17	0.95	0.57	0.75	0.83	0.84	0.82	0.55	1.14	1.09	0.93	0.82
000	1.04	0.88	0.70	0.78	0.76	0.86	0.88	0.54	0.91	0.89	0.90	0.72
000	0.86	0.87	0.58	0.80	0.77	0.76	0.76	0.58	0.77	0.67	0.81	0.71
q	1.01	0.83	0.60	0.83	0.81	0.90	0.85	0.53	0.92	0.87	0.90	0.77
000	1.02	0.95	0.55	0.79	0.78	0.90	0.85	0.49	0.91	0.88	0.86	0.82
p	0.99	0.75	0.58	0.81	0.80	0.86	0.86	0.56	0.89	0.86	0.97	0.78

Table 2.10: Photometry, Velocities and Abundances

Star	V	B-V	Vr	Mg+2Fe	co
NGC2141					
5003	13.18	1.37	23.8	2.97	001
4019	13.60	1.44	19.6	3.	002
5013	13.96	1.25	16.6	3.02	004
4032	14.05	1.21	27.0	2.67	006
4025	14.06	1.28	11.7	2.93	007
3274	14.68	1.17	10.4	2.66	010
2142	14.76	0.92	47.7	2.55	011
2444	14.78	0.93	3.3	2.62	013
3253	14.84	1.03	5.1	2.64	016
2329	14.87	0.97	-10.0	2.66	017
2210	14.92	1.16	-8.2	3.29	019
3436	14.95	1.05	22.6	2.64	021
3234	14.95	1.09	-4.0	2.64	022
3116	15.19	1.10	17.7	2.7	023
3429	15.60	1.04	13.2	2.87	026
NGC2158					
4269	12.91	1.62	13.3	3.	000
1116	13.21	1.45	18.0	2.8	000
3132	12.92	1.39	15.7	2.8	000
2316	14.13	1.38	0.2	3.18	000
4512	13.63	1.34	27.4	2.86	000
24c	13.17	1.22	18.6	2.7	000
2287	14.12	1.17	9.1	2.69	000
3401	14.39	1.16	-1.9	2.76	000
3415	14.42	1.22	17.6	2.9	000
2416	14.46	1.21	23.2	2.73	000
1325	14.63	1.04	8.5	2.56	000
1502	14.84	0.95	22.7	2.68	000
1515	14.84	0.93	5.2	2.48	000
4508	14.89	0.93	19.9	2.53	000
4413	14.91	0.95	13.1	2.57	000
1310	15.00	0.84	27.2	2.58	000
4320	15.02	1.01	2.6	2.57	000
2520	15.23	0.86	22.0	2.6	000
3413	15.36	0.90	15.5	2.64	000
4401	15.37	0.96	-0.6	2.71	000
NGC2204					
4132	11.18	1.74	5.3	2.47	000
2120	11.66	1.20	31.5	2.77	000
4137	11.76	1.55	63.3	2.75	000
4212	12.36	0.90	9.9	2.65	000
1320	12.62	1.01	74.2	2.56	000
3207	12.69	0.99	-4.3	2.57	000
1136	12.71	1.66	119.3	2.75	000
1129	12.71	1.07	73.3	2.58	000
2212	12.79	1.10	53.0	2.6	000
2136	13.06	1.05	62.8	2.48	000
3145	13.11	0.92	14.7	2.66	000
3215	13.68	1.00	66.0	2.42	000

Star	V	B-V	Vr	Mg+2Fe	co
4216	13.70	0.97	66.4	2.46	000
1133	13.76	0.92	68.0	2.47	000
4210	13.78	0.90	26.8	2.73	000
2229	13.81	0.87	74.3	2.47	000
1212	13.87	0.86	89.5	2.45	000
3205	13.88	0.87	67.9	2.49	000
4116	13.95	0.90	35.7	2.65	000
4123	13.97	0.88	-24.2	2.5	000
NGC2243					
2141	14.89	0.86	88.0	2.44	000
3312	14.11	0.82	42.5	2.68	000
3128	14.03	0.79	-12.3	2.68	000
4303	13.74	0.85	72.3	2.51	000
4137	13.71	0.88	51.9	2.44	000
2308	13.62	0.89	46.6	2.44	000
2245	14.20	0.91	58.4	2.48	000
3110	13.72	0.88	55.5	2.51	000
3316	13.76	0.99	64.6	2.56	000
2314	13.68	0.99	51.5	2.48	000
1219	11.81	1.02	78.6	2.77	000
4110	12.89	1.04	73.2	2.59	000
4209	12.11	1.30	44.0	2.86	000
NGC2477					
es399	9.65	1.65	22.3	2.98	000
h2117	9.90	1.61	7.7	2.99	000
es602	10.75	1.22	-0.8	2.72	000
es785	10.81	1.29	-0.7	2.74	000
es920	11.42	1.28	2.7	2.74	000
es956	11.43	1.14	2.4	2.68	000
es915	11.49	1.14	-5.0	2.67	000
es879	11.69	1.76	49.7	2.87	000
es752	11.70	1.06	16.8	2.7	000
es270	12.05	0.92	26.6	2.64	000
es430	12.06	0.92	-6.2	2.61	000
es396	12.18	0.94	-0.1	2.65	000
es902	12.20	0.85	-85.6	2.59	000
es911	12.28	0.88	-11.1	2.54	000
es272	12.33	0.90	5.7	2.61	000
es959	12.54	1.01	-26.2	2.48	000
es696	12.55	0.90	7.4	2.61	000
es913	12.63	0.90	-2.9	2.55	000
NGC2506					
3254	11.08	1.33	77.0	2.83	0.20
2122	11.69	1.11	71.1	2.58	0.9
2212	11.95	1.06	65.5	2.62	0.95
3204	12.67	0.86	72.7	2.48	0.93
1112	12.95	0.95	70.9	2.56	0.7
2364	13.04	0.84	60.1	2.44	0.92
4376	13.04	0.96	64.7	2.56	0.86
2309	13.07	0.94	54.2	2.53	0.9
3231	13.12	0.94	75.4	2.52	0.91

Star	V	B-V	Vr	Mg+2Fe	co
4240	13.12	0.92	73.0	2.45	0.79
1325	13.17	0.90	60.3	2.49	0.79
2480	13.18	0.90	64.6	2.58	0.92
23101	13.20	0.94	47.4	2.52	0.88
3265	13.21	1.00	57.3	2.46	0.91
3324	13.27	0.93	63.9	2.52	0.77
3359	13.27	0.91	75.9	2.58	0.94
4109	13.77	0.80	85.3	2.6	0.73
4274	13.78	0.90	80.0	2.55	0.8
3271	14.00	0.89	59.4	2.41	0.94
1301	14.64	0.83	64.9	2.52	0.80
47 Tuc					
W3	11.88	1.53	-18.9	2.83	000
3086	12.09	1.37	9.2	2.86	000
3027	12.11	1.46	-3.4	2.77	000
W280	12.24	1.35	-12.3	2.66	000
4004	12.33	1.37	-14.8	2.69	000
1031	12.37	1.37	-0.2	2.8	000
3023	12.46	1.31	-14.4	2.61	000
LE346	12.48	1.36	-25.2	2.59	000
N1108	12.55	1.25	-157.6	2.29	000
LE343	12.59	1.24	-17.4	2.64	000
LE354	12.67	1.25	-172.7	2.41	000
W92	12.81	1.21	-14.4	2.53	000
3006	12.84	1.18	-18.6	2.63	000
3016	13.66	1.03	82.9	2.08	000
792	11.82	1.58	-12.3	2.77	I
542	11.83	1.59	-13.9	2.79	I
265	11.83	1.58	-11.9	2.65	TiO
481	11.83	1.58	-19.6	2.73	P3
343	11.86	1.66	-19.8	2.81	I
426	11.88	1.54	-13.3	2.78	TP3
525	11.91	1.48	-6.6	2.8	IP3
870	11.94	1.52	-19.0	2.77	I
410	12.04	1.46	-19.4	2.79	TvP3
559	12.08	1.50	-27.9	2.71	TPIP3
342	12.21	1.39	-22.4	2.74	P3
431	12.23	1.36	-24.3	2.76	P3
484	12.34	1.45	-10.4	2.73	P3
390	12.36	1.34	-17.2	2.79	P3
355	12.43	1.33	-34.5	2.64	000
341	12.46	1.24	-10.0	2.68	P3
55	12.47	1.32	-18.6	2.72	P3
523	12.50	1.23	-24.6	2.58	P3
769	12.57	1.28	-80.7	2.68	I
573	12.69	1.18	-2.5	2.66	PI
907	12.81	1.22	-31.0	2.55	I
371	12.82	1.24	-23.3	2.61	000
514	12.90	1.25	-26.7	2.53	P3
863	13.06	1.18	-6.8	2.58	I
cfxen	0.00	0.00	0.0	2.64	cen

Star	V	B-V	Vr	Mg+2Fe	co
458	11.66	1.72	-46.9	2.48	cfx
624	12.08	1.31	64.5	2.8	cfx
191	12.11	1.49	-7.5	2.95	cfx
637	12.17	1.35	-16.7	2.75	cfx
4	12.29	1.36	-25.8	2.78	cfx
6	12.29	0.49	-13.6	2.4	cfx
680	12.34	1.53	-24.6	2.59	cfx
195	13.55	1.11	-18.4	2.59	cfx
NGC1851					
336	14.98	0.99	313.1	2.28	000
249	15.33	1.01	0.0	2.3	000
399	15.13	1.02	233.9	2.49	000
136	14.66	1.03	315.9	2.52	000
41	14.96	1.03	330.0	2.28	000
319	14.85	1.14	318.7	2.65	000
126	14.29	1.20	316.3	2.57	000
107	14.50	1.21	289.8	2.48	000
333	14.05	1.27	270.6	2.3	000
279	13.93	1.28	324.3	2.49	000
151	13.71	1.35	303.1	2.48	000
3	13.60	1.38	289.0	2.42	000
112	13.80	1.47	312.1	2.44	000
262	13.30	1.55	333.6	2.53	000
395	13.55	1.58	310.4	2.63	000
294	13.40	1.59	319.8	2.64	000
329	13.45	1.60	305.8	2.65	000
168v	13.19	1.72	234.6	2.7	000
M4					
139	14.88	1.36	58.0	2.64	000
123	13.90	1.00	73.0	2.52	000
246	14.54	1.12	108.0	2.84	000
248	14.57	0.95	-9.1	2.5	000
297	13.51	0.59	71.6	2.7	000
308	15.25	0.71	53.8	2.58	000
4611	10.85	1.47	70.1	2.65	000
4613	10.93	1.54	71.9	2.83	000
4624	12.71	0.95	86.6	2.47	000
4621	13.35	0.51	67.9	2.39	000
4602	13.01	0.97	90.6	2.36	000
4414	11.80	0.93	68.4	2.4	000
4415	12.58	0.98	64.4	2.41	000
NGC288					
096	12.69	1.54	-57.5	2.63	000
078	12.88	1.44	-57.7	2.61	000
213	13.03	1.32	-59.2	2.6	000
219	13.43	0.86	-43.5	2.39	000
186	13.47	1.16	-67.5	2.5	000
231	13.53	1.14	-47.7	2.45	000
307	13.60	1.20	-31.3	2.38	000
277	13.74	1.11	-56.1	2.42	000
007	13.81	1.16	-70.4	2.46	000

Star	V	B-V	Vr	Mg+2Fe	co
070	13.96	1.07	-64.5	2.46	000
178	14.09	1.09	-52.5	2.29	000
206	14.10	0.86	-92.2	2.46	000
131	14.51	0.88	-64.8	2.44	000
019	14.70	0.94	-57.8	2.49	000
027	14.94	0.94	-102.5	2.36	000
NGC362					
2124	14.99	0.66	150.7	2.38	000
2212	14.56	0.79	196.7	2.66	000
2401	14.24	0.86	196.5	2.67	000
2309	14.83	0.87	184.2	2.56	000
2223	14.78	0.87	240.9	2.38	000
pe55	13.23	0.88	114.9	2.54	000
pe63	14.85	0.89	169.2	2.52	000
pe45	14.24	0.98	216.0	2.57	000
2302	13.96	1.03	199.7	2.72	000
2108	13.77	1.07	204.2	2.61	000
2113	14.64	1.07	30.5	2.45	000
pe65	13.66	1.13	199.1	2.69	000
2213	13.43	1.17	229.8	2.46	000
2423	12.81	1.44	207.3	2.66	000
1441	12.71	1.58	222.8	2.49	000
2115	13.00	1.61	219.8	2.48	000
cent	100.00	0.00	155.7	2.44	000
NGC6356					
000	0.00	1.23	52.6	2.77	JK
115	16.10	1.25	54.6	2.62	000
000	0.00	0.00	98.6	2.46	000
113	15.77	1.16	54.6	2.74	000
111	15.67	1.26	36.9	2.68	000
000	0.00	1.26	54.7	2.71	JK
104	16.32	1.15	87.5	2.7	000
000	0.00	1.29	57.2	2.58	JK
162	14.72	0.63	-94.4	2.18	000
000	0.00	0.00	16.6	2.46	000
000	0.00	0.87	38.3	2.48	JK
000	0.00	0.00	55.2	2.64	000
37	15.23	1.54	42.5	2.61	000
000	0.00	0.00	57.9	2.33	000
80	15.36	1.52	67.1	2.89	000
NGC6440					
a	0.00	1.67	-9.6	2.65	JK
c	0.00	1.64	-2.7	2.68	JK
y	0.00	0.00	-0.9	2.38	000
b	0.00	1.30	-30.1	2.8	JK
x	0.00	0.00	28.4	2.48	000
l	0.00	0.77	-69.9	2.57	JK
ce	0.00	1.07	-60.6	2.48	JK
3	0.00	0.96	-40.3	2.53	JK
f	0.00	0.00	12.0	2.52	000
e	0.00	0.00	26.3	2.77	000

Star	V	B-V	Vr	Mg+2Fe	co
d	0.00	1.62	-46.5	2.87	JK
NGC6528					
000	0.00	0.00	5.1	2.43	000
I-7	16.38	0.91	166.3	2.71	000
000	0.00	0.00	220.1	2.54	000
I-6	16.01	1.21	213.1	2.64	000
000	0.00	0.00	202.3	2.67	000
I-8	15.45	0.34	179.9	2.6	000
000	0.00	0.00	-70.7	2.77	000
000	0.00	0.00	13.0	2.5	000
000	0.00	0.00	212.7	2.73	000
000	0.00	0.00	218.4	2.69	000
000	0.00	0.00	213.0	2.58	000
NGC6553					
III-5	0.00	0.00	172.1	2.86	000
000	0.00	0.00	69.3	2.73	000
II-4	15.60	1.51	63.3	2.83	000
000	0.00	0.00	35.6	2.66	000
III-15	15.60	1.48	45.6	2.64	000
III-10	16.73	0.80	8.7	2.3	000
000	0.00	0.00	55.7	2.72	000
000	0.00	0.00	196.7	2.52	000
NGC6624					
I102	15.82	1.15	-5.5	2.62	000
0000	0.00	0.00	28.5	2.34	000
0000	0.00	0.00	11.5	2.63	000
I130	16.10	1.76	22.9	2.46	000
U	15.41	1.61	-20.0	2.53	000
I40	16.50	0.62	-53.9	2.33	000
I43	15.86	0.83	79.6	2.4	000
0000	0.00	0.00	-29.1	2.85	000
h	12.05	1.03	13.0	2.74	000
II28	15.93	0.86	33.5	2.49	000
III132	15.17	1.67	35.3	2.96	000
0000	0.00	0.00	-58.3	2.78	000
e	14.97	1.14	-93.6	2.61	000
K	17.78	0.49	37.6	2.71	000
III7	14.72	1.33	50.3	2.7	000
III12	14.86	1.23	-101.0	2.68	000
III125	13.80	1.14	-79.5	2.64	000
0000	0.00	0.00	46.9	2.57	000
III31	14.03	1.19	-89.8	2.81	000
0000	0.00	0.00	75.3	3.03	000
0000	0.00	0.00	2.3	2.75	000
0000	0.00	0.00	33.6	2.37	000
A	13.09	1.50	-8.2	2.62	000
0000	0.00	0.00	20.3	2.55	000
IV122	15.00	1.12	8.6	2.51	000
0000	0.00	0.00	58.9	2.85	000
IV155	16.25	1.06	8.8	2.53	000
0000	0.00	0.00	169.9	2.94	000

Star	V	B-V	Vr	Mg+2Fe	co
0000	0.00	0.00	-81.9	2.44	000
0000	0.00	0.00	20.0	2.88	000
0000	0.00	0.00	-51.1	2.69	000
0000	0.00	0.00	-113.8	2.96	000
0000	0.00	0.00	54.4	3.23	000
0000	0.00	0.00	-15.8	3.32	000
0000	0.00	0.00	-168.8	2.61	000
0000	0.00	0.00	83.6	2.79	000
0000	0.00	0.00	63.2	2.64	000
0000	0.00	0.00	-51.4	2.79	000
0000	0.00	0.00	22.9	2.98	000
0000	0.00	0.00	38.0	2.56	000
0000	0.00	0.00	-34.8	2.72	000
0000	0.00	0.00	50.9	2.43	000
NGC6637					
00000	0.00	0.00	75.9	2.49	000
III10	14.15	1.66	18.1	2.66	000
00000	0.00	0.00	34.8	2.75	000
III34	14.44	1.40	16.0	2.53	000
00000	0.00	0.00	-51.1	2.82	000
III41	12.83	0.64	-30.3	2.36	000
II41	16.11	1.05	31.5	2.44	000
00000	0.00	0.00	0.7	2.49	000
00000	0.00	0.00	-0.2	2.61	000
II16	16.66	0.69	54.7	2.57	000
I43	12.88	1.90	207.4	2.49	000
I32	14.25	1.59	32.1	2.64	000
00000	0.00	0.00	-15.4	2.98	000
00000	0.00	0.00	-94.8	2.45	000
00000	0.00	0.00	-45.7	2.6	000
00000	0.00	0.00	-114.8	2.48	000
00000	0.00	0.00	-110.0	2.45	000
19	16.67	0.91	-50.0	2.49	000
II12	16.33	0.55	19.4	2.44	000
I8	15.80	0.85	58.8	2.54	000
00000	0.00	0.00	-52.4	2.54	000
00000	0.00	0.00	-9.5	2.55	000
II35	12.71	0.44	4.7	2.6	000
III2	15.02	1.33	-126.9	2.52	000
M28					
RC461	15.46	1.23	21.0	2.43	83%
a	14.94	1.35	54.4	2.64	0%
b	14.12	1.79	45.5	2.89	0%
000	0.00	0.00	151.1	2.14	000
000	0.00	0.00	73.4	2.91	000
d	14.11	2.09	133.9	2.89	0%
c	15.45	1.27	-220.9	2.62	0%
000	0.00	0.00	105.5	2.73	000
000	0.00	0.00	53.7	2.52	000
000	0.00	0.00	79.3	2.72	000
000	0.00	0.00	45.8	2.87	000

Star	V	B-V	Vr	Mg+2Fe	co
000	0.00	0.00	19.3	3.19	000
000	0.00	0.00	-14.7	2.53	000
e	14.87	1.47	215.3	2.67	0%
f	14.45	1.77	26.3	2.4	0%
000	0.00	0.00	167.9	2.65	000
2-108	15.91	1.30	149.4	2.39	59%
g	14.79	1.95	20.0	2.89	0%
000	0.00	0.00	230.0	2.57	000
000	0.00	0.00	229.0	2.65	000
2-109	14.89	1.51	15.3	2.42	85%
i	14.12	1.77	-72.5	2.53	0%
z'	15.62	0.34	33.9	2.2	0%
000	0.00	0.00	76.9	2.68	000
000	0.00	0.00	76.2	2.25	000
k	14.46	1.96	11.6	2.81	0%
l	14.71	1.81	7.1	2.83	0%
000	0.00	0.00	57.5	2.54	000
000	0.00	0.00	143.8	2.43	000
n	14.66	1.63	204.5	2.78	33%
m	13.88	1.89	-43.4	2.78	19%
000	0.00	0.00	83.6	2.66	000
000	0.00	0.00	267.6	2.83	000
000	0.00	0.00	89.9	2.78	000
000	0.00	0.00	156.4	2.38	000
q	14.71	1.56	76.8	2.76	2%
000	0.00	0.00	91.5	2.77	000
p	15.36	1.37	6.0	2.71	0%

members of a cluster), show variations in MgH strength, variations that increase for increasing $[\text{Fe}/\text{H}]$. From the different clusters we obtain: $\sigma_{MG} = 0.03, 0.04$, and 0.07 , $\sigma_{Fe5270} = 0.04, 0.05$, and 0.06 , $\sigma_{Fe5335} = 0.04, 0.05$, and 0.07 for $[Fe/H] = -1.7, -1.0$ and 0.0 , respectively. These uncertainties, combined with the errors in the photometry discussed above, translate into total errors for the individual metallicity derived for a single star of: $\sigma_{[Fe/H]} = 0.10, 0.15$, and 0.25 for $[Fe/H] = -2.0, -1.0, 0.0$, respectively. These values are checked by computing the mean metal abundances for the clusters. All the clusters abundances are recovered, with increasing dispersion for increasing metallicities. The zero point error of the whole abundance scale is estimated to be 0.15 dex.

2.7. The Calibration

2.7.1. $H\beta$

This index is not correlated with metallicity. Some of the giants in metal rich globulars have strong $H\beta$. There is only a weak correlation with temperature for stars with $(B-V)_0 \leq 1.15$, a correlation that disappears for cooler stars, where $H\beta$ is not present. Figure 1 shows the strength of $H\beta$ vs color for cluster giants, the right and left panels correspond to open and globular clusters, respectively.

2.7.2. Fe lines

We have explored the dependence of all of the indices on metallicity. Of the Fe features listed in table 7, the most sensitive to metallicity are Fe5270 and Fe5335. This is consistent with the findings of Friel (1987), and Burstein et al. (1984). Furthermore, the strength of these features is nearly independent of

Figure 2.1 Strength of the $H\beta$ line at 4860 Å vs dereddened color for globular (right panel) and right clusters (left panel). The symbols for the right panel are: NGC2141, NGC2158, NGC2204, NGC2243, NGC2477, NGC2506. The symbols for the left panel are: 47Tuc, NGC6624, NGC6637, NGC288, NGC362, NGC1851.

color (temperature) for the giants considered here. However, the iso-abundance lines converge for abundances close to Solar.

Figures 2 to 7 show the different Fe line indices vs dereddened color. For $(B-V)_0 \geq 1.6$, the presence of TiO bands in the spectra confuse the ranking of clusters according to metallicity. The iron indices Fe4680 (not shown) and Fe5400 (figure 7) are relatively sensitive to metallicity, for some restricted color ranges, but are not as good as Fe5270 (figure 2) and Fe5335 (figure 3). The indices Fe4920 (figure 5) and Fe5011 (figure 4) are not very sensitive to measure metallicity. Some authors found that adding the weak lines would produce an index sensitive to metallicity. This is not the case here, we find that adding weak lines produces a very noisy metal abundance indicator. The use of Fe5270 and Fe5335 is preferred. This choice is also motivated by the fact that the spectra from all the observing runs include the Fe5270 and Fe5335 features. Instead, the Fe4680 line falls beyond the wavelength coverage of the Argus and MMT data, while the Fe5400 feature is not included in the 90" and MMT data.

2.7.3. Mg features

The Mg triplet and MgH band-head at 5170 Å are also sensitive to metallicity, even though they also show a strong dependence on temperature and luminosity. Several indices have been defined to measure this feature strength: Mgb, Mg2, MgH, Mg1, and Mg as listed in table 7. These different passbands give different dependences to metal abundance, gravity and temperature. The Mgb and Mg2 indices measure the strength of the magnesium triplet at 5175Å.

Figure 2.2 Same as figure 1 for the Fe line at 5270 Å.

Figure 2.3 Same as figure 1 for the Fe line at 5335 Å.

Figure 2.4 Same as figure 1 for the Fe line at 5011 Å.

Figure 2.5 Same as figure 1 for the Fe line at 4920 Å.

Figure 2.6 Same as figure 1 for the Fe line at 4980 Å.

Figure 2.7 Same as figure 1 for the Fe line at 5400 Å.

The MgH index measures the strength of the magnesium hydride molecule. The Mg index as defined Friel (1987) has a wider passband, which reduces the metallicity sensitivity, but it is more useful for lower S/N spectra.

Figures 8 and 10 plot the Mg indices vs color for selected globular and open cluster giants. Most of the red giants in open clusters around $(B-V)_0 = 0.9$ are in the RGB clump, while the upper RGB of open clusters is not as well defined as the RGBs of globular clusters.

The onset of the MgH in globular cluster giants is clearly seen at $B-V_0 = 1.15$ (figure 9).

Direct comparison of figures 9 and 10 shows that the MgH feature is much stronger in globular clusters than in open clusters with similar $[Fe/H]$.

As discussed above, the scatter in the Mg strength of giants within a cluster increases for increasing metallicity. We argue that it is intrinsic, and not due to S/N or measurement errors. For example, the giants of 47Tuc are measured several times, their S/N is very high, and the indices repeat almost very nicely. In fact, the indices should be better measured for more metal rich stars with stronger lines.

2.7.4. Magnesium vs Iron

Figure 11 shows the strength of the Mg indices vs the sum of the Fe5270 and Fe5335 indices for different groups: field stars, metal rich open clusters, metal poor globulars and metal rich globulars. This plot is one of the arguments to associate bulge field stars with metal rich globulars, as we will discuss in the next chapters.

Figure 2.8 Same as figure 1 for the Mg index.

Figure 2.9 Comparison of the Mg1, Mg2, Mgb, and MgH indices *vs* $(B-V)_0$ for giants in selected globular clusters.

Figure 2.10 Comparison of the Mg1, Mg2, Mgb, and MgH indices *vs* $(B-V)_0$ for giants in selected open clusters.

2.8. The Mg+2Fe Combined Index

The final abundances will be derived using the sum of the indices Mg, Fe5270 and Fe5335. In spite of the different behaviour of these indices, this particular combination was found to be the best among the ones analyzed, to measure metallicities. We decided to use the sum rather than calibrate each index separately, because this makes more sense for the lower S/N spectra. Figure 12 shows the Mg+2Fe combined index *vs* dereddened color for the observed giants in open and globular clusters. Figure 13 is the same diagram for the giants and dwarfs with accurate metallicities, spectral types and colors from Friel (1987) listed in table 8. The main ridge lines defined by the main sequence stars is also in excellent agreement with the locus defined by Friel (1987).

The fiducial lines shown in figure 12 have been fitted by eye. For the metal rich end, we have also used the results for the clusters studied in the next chapter to place the fiducial lines. The useful range of this calibration is from $(B-V)_0 \sim 0.9$ to ~ 1.6 . For redder giants, the TiO bands affect the Mg index.

2.8.1. Standard clusters.

For the open clusters, we will adopt the scale of Friel & Janes (1993), as this is one of the largest, most homogeneous spectroscopic determination of abundances and velocities available for open clusters. Other studies, like the photometric study of Geisler, Claria & Minniti (1993) agree with this scale. For the globular clusters, we have adopted the Zinn scale, as revised by Armandroff (1989) and Armandroff & Zinn (1991). The only cluster for which a different

Figure 2.11 Strength of Mg vs Fe5270+5335 indices for giants in different groups of clusters: open clusters (a), metal poor globulars with $[\text{Fe}/\text{H}] \leq -1$ (b), intermediate metallicity clusters with $-1 \leq [\text{Fe}/\text{H}] \leq -0.6$ (c), and metal rich globulars with $[\text{Fe}/\text{H}] \geq -0.6$.

Figure 2.12 Combined $\text{Mg} + 2\text{Fe}$ index vs $(B-V)_0$ for open and globular cluster giants. This index is used to determine metallicities for the program giants. The isoabundance lines of the calibration plotted correspond to (from top to bottom) $[\text{Fe}/\text{H}] = 0.0, -0.5, -1.0, -1.5,$ and -1.75 .

Figure 2.13 Mg and $Mg+2Fe$ vs $(B-V)_0$ for the field stars from the lists of Friel (1987). The symbols are: $\blacktriangle$ dwarfs, $*$ K giants with uncertain metallicities, and $\circ$ K giants with well known abundances (larger circles correspond to more metal rich giants).

metallicity is assumed is M4 , for which recently Drake et al. (1992) have determined $[\text{Fe}/\text{H}] = -1.05 \pm 0.02$, from high dispersion echelle spectra and model atmospheres of 4 giants.

There are some clusters that have been well studied, and can be used as standards. There are some other clusters for which the metallicities are less well known. We will define a grid of standard clusters, and obtain the metallicities of less well studied clusters from there. With this new abundances, we will redefine the grid, and proceed to get metal abundances for the bulge giants. The standard clusters are 47Tuc, NGC288, NGC362, NGC1851, M3, M4, M71, M15, M22, and NGC6356.

The cluster M4 is taken to be a standard cluster, even though a wide range of metallicities has been published. The position of the giants in the $\text{Mg}+2\text{Fe}$ vs $\text{B}-\text{V}$ and $\text{Mg}+2\text{Fe}$ vs $\text{J}-\text{K}$ diagrams support the recent high quality metallicity by Drake et al. (1992), and we will adopt $[\text{Fe}/\text{H}] = -1.05$ for this cluster, and not the Zinn (1985) value. The near-IR photometry supports also this higher metallicity for M4 (FCP83, Minniti et al. 1993).

The cluster NGC1851 is also taken as a standard cluster, even though its abundance is controversial (see Armandroff & DaCosta 1991). We have adopted $[\text{Fe}/\text{H}] = -1.1$ for this cluster.

The cluster NGC6356 is well defined, with several giants measured. The same is true for the cluster NGC6624. The cluster NGC6356 was adopted as calibrator because it is the most metal rich cluster listed in the sample of Brodie & Huchra (1990), and it is also the cluster with strongest $\text{Mg}2$ index in the sample of Burstein et al. (1984).

2.8.2. Final globular cluster abundances

Using the mean lines defined by the standard clusters, we proceed to the determination of metallicities for the less well studied clusters. These are NGC6401, NGC6440, NGC6553, NGC6528, NGC6637, NGC6642, NGC6624, and M28. The clusters NGC5466, NGC6366, and NGC6402 have very few stars measured and we prefer to wait for more observations before deriving a metallicity. As argued before, the dispersion of giants around the mean for each cluster is a function of cluster metallicity. Figure 12 shows this trend. A good description of the error in the metallicity determinations is given by $\sigma_{[Fe/H]} = 0.15$ for $[Fe/H] \leq -1.0$, and $\sigma_{[Fe/H]} = 0.1[Fe/H] + 0.25$. We estimate that the present calibration can be applied for the range from -2.0 dex to ≤ 0.5 dex, being uncertain for higher than Solar metallicities.

The final abundances for non-standard clusters observed here are listed in table 11, along with the number of stars considered, and the rms errors from the individual stars within a cluster. The metallicities of 5 additional clusters (HP1, Pal6, NGC6642, NGC6325, and NGC6517) are measured in the next chapter with the aid of IR photometry.

2.8.3. Comparison with Previous Abundance Determinations

We derive $[Fe/H] = -1.25 \pm 0.2$ for M28. This confirms its assignment to the halo population of globulars, despite its recently measured proper motion that suggests a disk-like orbit (Cudworth 1993).

Table 2.11

DERIVED CLUSTER METALLICITIES

CLUSTER	[Fe/H]	sigma
N6624	-0.40	0.3
N6637	-0.80	0.3
M28	-1.25	0.2
N6553	-0.30	0.3
N6528	-0.25	0.3
N6642	-1.40	0.3

The cluster NGC6637 is not as metal rich as suggested by the Zinn & West (1982) scale. We find $[\text{Fe}/\text{H}] = -0.8 \pm 0.2$, consistent with the IR photometry of Frogel, Persson & Cohen (1983), and the more recent photometry of Davidge & Simmons (1992). The large apparent scatter is because the mean cluster velocity matches the mean velocity expected for the background giants, then there is uncertain field contamination. The presence of a single very metal poor halo star or metal rich bulge star would bias this result.

The cluster NGC6642 has no published CMD. The only photometry is that of variables in the field of the cluster by Hazen et al. (1993). Recently, we have obtained an IR CMD. The published metallicity is $[\text{Fe}/\text{H}] = -1.30$ (Table 3), but determined from integrated properties. The present value $[\text{Fe}/\text{H}] = -1.4 \pm 0.2$ is in good agreement. Note that Hazen et al. (1993) revised the distance modulus for this cluster by 0.8 magnitudes, obtaining $(m-M)_V = 15.6$.

For HP1 we find $[\text{Fe}/\text{H}] = -0.5 \pm 0.2$, consistent with the metallicity of Armandroff & Zinn (1988), confirming their result that the Webbink (1985)

abundance $[\text{Fe}/\text{H}] = -1.68$ was much too low. Note that we have adopted a higher reddening for this cluster, $E(\text{B}-\text{V}) = 1.5$. Recently, Mallen-Ornellas & Djorgovski (1993) obtained $E(\text{B}-\text{V}) = 2.1 \pm 0.2$ for HP1, a value higher than that of Armandroff & Zinn (1988).

The abundances for the rest of the clusters are in agreement with the values compiled by Armandroff (1989).

2.8.4. Comparison with Model Atmosphere Results

The empirical grid obtained can be compared with the predictions of different model atmospheres, to gain insight on the underlying physical processes, as the relative importance of $\log g$, T_{eff} , and $[\text{Fe}/\text{H}]$. Recently, Barbuy et al. (1992, 1993) and Gulati et al. (1993) computed the Mg and Fe indices as functions of these three parameters for model atmospheres of Bell (1989) and of Kurucz (1993), respectively. The results of these authors agree with each other, so we will make the comparison to our data with the Barbuy et al. (1992) results. They conveniently present the results in graphic form for different combinations of $[\text{Fe}/\text{H}]$, T_{eff} , and $\log g$ for the range of interest.

The indices defined by Barbuy et al. (1992) are similar to ours, aside from a constant term. To make the comparison, we have translated the T_{eff} to colors via the relationships given by McWilliam (1990) for B-V and J-K, valid for giants with near Solar metallicity. The slope of the isoabundance lines and their spacing are consistent with our empirical calibration. Also, the mean line for $[\text{Fe}/\text{H}] = 0.5$ follows the extrapolation of the more metal poor lines.

This is the confirmation that the grid still holds for stars more metal rich than Solar. Note that in our calibration the $[\text{Fe}/\text{H}] = 0.5$ line was poorly defined by standards. However, the model atmosphere results confirm that the indices do not lose sensitivity or turn over for the metal rich end (although note the scatter increasing with metallicity discussed below).

We also confirm the results of Barbuy et al. (1992, their figure 13) in the onset of MgH in globular cluster giants occurs at $T_{\text{eff}} = 4500^\circ\text{K}$, or $(B-V)_0 = 1.15$, $(J-K)_0 = 0.72$. The same seems to be true for bulge giants also (chapters 4, 5 and 7).

2.8.5. The open clusters

Most of the giants observed in the open clusters are in the RGB clump. In the bulge, these RHB-clump stars are too faint to have been included in our samples (chapters 4 to 6). Thus, obtaining metal abundances for the open clusters is beyond the scope of this thesis. We merely used them for comparison, the opens observed here have well determined metallicities (e.g. Friel & Janes 1993). However, we note that the Mg index strength is systematically weaker than that predicted for the globulars at the same metallicity. This is the same effect found by Friel & Janes (1993). This effect can be interpreted in terms of the findings of Edvardsson et al. (1993).

2.9. Conclusions

$\text{Mg}+2\text{Fe}$ can be used to determine metallicity, being sensitive to metallicity from $[\text{Fe}/\text{H}] = -2$ to about 0.5 dex. The scatter in the derived metallicities

increases considerably for clusters like 47Tuc or more metal rich. This effect can be attributed to increased molecular opacity, (DalleOre & Peterson 1992, McWilliam & Rich 1993). A new improved method should be developed for metal rich stars. The Ca II triplet (Armandroff & Zinn 1989, Suntzeff et al. 1993) looks very promising, even though there is a decrease in sensitivity for the metal rich domain, it still looks like one of the best methods.

A grid was defined. This grid was constructed to determine abundances for bulge giants. Note the very important assumption is that the globulars and the bulge-halo population had the same chemical enrichment history. If true, this would ensure that even when the $[X/Fe]$ ratios change with $[Fe/H]$, they do so in the same way in the globulars and bulge-halo giants. Note that the open clusters do not comply with this condition, and are therefore not considered as calibrators.

Good agreement was found with previous calibrations of these indices. Excellent agreement is found with the predictions of model atmosphere indices. In particular, the onset of MgH is clearly seen in the bulge and in the globular cluster giants.

We have found that in general, the globular and open clusters do not follow the same calibration. The present data supports the conclusions of Friel & Janes (1993) in that Mg strength is dependent on open cluster age as well as temperature and metallicity. The red giants of open clusters have weaker Mg absorption than globular cluster giants of the same metallicity. We agree with the speculation of Friel & Janes (1993) that different $[Mg/Fe]$ ratios are the

cause of the differences between the globular cluster scale and the open cluster
+ field stars scale.

3. NEAR-IR PHOTOMETRY OF GALACTIC GLOBULAR CLUSTERS AND BULGE FIELDS

We present K vs J-K color magnitude diagrams for Galactic globular clusters projected onto the bulge. These color-magnitude diagrams reach ~ 2 magnitudes below the horizontal branch at the distance of the bulge. In particular, the clusters HP1, ESO45-SC11, NGC6287, NGC6401, NGC6642, Pal6 and UKS1 have no previously published CMDs.

We also compare the position of the giant branches with respect to the standard globular clusters M92, M4 and M22, and put all the clusters on a uniform scale. From existing models and observations, we adopt the calibration law $[Fe/H] = 5.0(J - K) - 5.60$ based on the color of the red giant branch at $K_0 = -5$, valid between $[Fe/H] = -2.3$ and 0.5. Reddenings are derived for the less studied clusters, based on the position of the red giant branches in the near-IR color magnitude diagrams. Pal6 turns out to be the most metal rich cluster of our sample, with $[Fe/H] = 0.2 \pm 0.3$.

The clusters TJ5, TJ15 and TJ16 are not detected. It is likely that these are not real globulars.

We present spectra for some bright members of several clusters selected from the IR photometry. The spectra give radial velocities to check membership. They also provide accurate abundances when coupled with the photometry.

A comparative study is made between the clusters and the bulge stellar population, using photometry in selected fields located a few arcminutes away from the cluster cores. Our major conclusion is that the bulge giants have

the same near-IR colors in the mean as the most metal rich globulars. A metallicity gradient is found, that supports previously published results from optical photometry.

3.1. Introduction

The study of globular clusters has given fundamental insight into the early formation of our Galaxy, and is one of the bases for the determination of ages and distances in many situations. The importance of the metal rich globulars in the context of Galactic studies is well summarized by Armandroff (1993). The clusters that are closer to the Galactic center ($R_{Gal} \leq 3$ kpc) are among the most poorly studied clusters, with heavy reddening and field contamination. It is important to refine our knowledge of the globular clusters, which constitute a very limited sample. For example, Zinn (1993) divides the cluster sample in several groups to study the process of cluster and Galaxy formation. The statistics in these groups would be much improved with the inclusion of several poorly studied clusters with $R_{Gal} \leq 3$ kpc.

For example, Hesser & Shawl (1985) compile different $[Fe/H]$ measurements for known Galactic globulars. For the globulars with multiple measurements, differences of 0.5–1.0 dex are not uncommon! Likewise, distance estimates are also uncertain. A comparison between the compilations of Webbink (1985) and of Thomas (1990) reveals that very often these inner clusters have values of R_{Gal} differing by factors of 2! It is extremely important then to refine the parameters for the clusters within 3 kpc of the Galactic center, to refine studies like that of

Zinn (1993). About 44% of the clusters within 3 kpc from the Galactic center do not have $[\text{Fe}/\text{H}]$ measurements (Zinn 1990).

Due to the higher contrast in the IR, crowding is less severe than in the optical passbands. This is due to the almost vertical RGB in the K, J–K color-magnitude diagrams (CMDs), contrasting with the optical CMDs, that bend over at the reddest and more metal rich stars. That results in a ~ 8 magnitude difference between the tip of the red giant branch (RGB) and the turn-off (TO) at K, while at V that difference is only about 5 mags for metal rich globulars.

This is the first report of our long term snapshot survey of globular clusters of the inner Galaxy. Our long term goals are twofold: to define better their distances, reddenings and metallicities, and to use them as references for the study of the underlying Galactic bulge population. In particular, we want to study the similarities and differences between the metal rich globulars and the bulge stellar population. The photometry is deep enough to include known RR Lyr variables in these clusters, which will give a measure of the distances. The K magnitudes of the brightest giants will also give another distance estimate. Reddenings and metallicities can be derived from the position of the cluster red giant branch. We will combine the IR photometry with already published optical photometry for better abundance determinations. Note that this is a snapshot survey, meaning that we seek to determine gross parameters for a large sample. Therefore, the data taking and reduction procedure were treated accordingly. The final photometric errors achieved here are never better than 0.03 magnitudes. This sample will help identify ideal cluster fields for deep photometric studies in the near-IR, seeking improved errors (≤ 0.01 mag).

The works of Frogel, Cohen & Persson (1981, 1983), Frogel, Persson & Cohen (1981) and references therein (referred collectively as FCP hereafter) give an enormous database of IR photometry of globular cluster giants, and, more importantly, they essentially defined the whole system. Other more recent near-IR CMDs of globular clusters published are those of M69 (Davidge 1991), NGC6306 (Davidge & Simmons 1992), and Ter2 (Christian & Friel 1992). Likewise, the K giants in the Galactic bulge were studied in the infrared by Frogel, Whitford & Rich (1984), and Davidge (1991), and the M giants by Frogel & Whitford (1987), Frogel et al. (1990). Although with single channel detectors it was only possible to observe relatively bright objects ($K \leq 13$), the works of Frogel and collaborators defined this whole area of study.

3.2. The Candidates

We have selected a large sample of globular clusters located within ~ 20 degrees of the Galactic center. These include a fair fraction of low latitude, heavily obscured clusters. The 20 clusters of this sample explore the whole range of metallicity for the cluster system, spanning from $[\text{Fe}/\text{H}] \approx -2.0$ to $+0.25$. The primary selection criteria was that the cluster be observable from Arizona; this limited our sample to clusters with $\delta \geq -30$. The secondary selection criteria was that the cluster had not been well studied. An additional criterion was that the clusters have large or unknown reddening. At the same time, we observed some bulge fields without clusters, which are not the main objects of study here, but which will be used occasionally for reference.

Table 3.1: OBSERVING RUNS

Dates	Fields Observed	Telescope
SPECTROSCOPY		
Jun 24/25 1991	M22,M4	MMT
May 24 1992	N6356,HP1,N6401,Pal6	MMT
Jun 6 1992	N6440,M22,M4	MMT
Jun 7 1992	N6325,N6517,N6642,N6284	90"
PHOTOMETRY		
Jun 2/5 1990	F588,F589	61"
Jun 18/19 1991	N6235,N6144,N6287,N6325,N6333,N6284,BW, N6401,Pal6,N6440,N6517,M22,N6642,N6638	90"
May 13/14 1992	N6356,ESO45,Ter2,N6293,HP1,SGR1,N6528	90"
Jun 8/9 1992	N6356,ESO45,N6293,UKS1,M92,F588,M4	90"

Table 3.2: CLUSTERS OBSERVED

Cluster	l	b	E_{J-K}	Dist	[Fe/H]	Source	Size	N
N6144	-8.1	15.7	0.20	9.5	-1.75	A90	8.5×2.5	0
ESO45	-8.1	12.1	0.17	10.3	-1.01	W85	7.5×2.5	0
N6235	-1.1	13.5	0.19	9.5	-1.40	A90	6.6×2.5	0
N6284	-1.7	9.9	0.16	10.3	-1.40	A90	6.0×2.5	4
N6287	0.1	11.0	0.28	7.2	-1.72	W85	6.0×2.5	0
N6293	-2.8	7.3	0.21	7.7	-1.92	A90	7.5×2.5	0
TJ5	-2.8	5.6	....	...	....	W85	5.0×2.5	0
N6325	1.0	8.0	0.48	6.2	-1.44	A90	6.0×2.5	2
TJ15	-1.1	6.5	....	...	....	W85	3.3×2.5	0
TJ16	-2.3	5.6	....	...	....	W85	3.3×2.5	0
N6333	5.5	10.7	0.19	7.5	-1.78	A90	6.6×2.5	0
N6356	6.7	10.2	0.15	16.7	-0.54	A90	7.5×2.5	12
HP1	-2.6	2.1	0.79	9.5	-0.56	AZ88	7.5×2.5	6
N6401	3.5	4.0	0.43	7.1	-1.01	W85	6.0×2.5	9
PAL6	2.1	1.8	0.81	5.9	0.22	W85	6.6×2.5	6
N6440	7.7	3.8	0.62	7.1	-0.34	A90	6.0×2.5	11
UKS1	5.1	0.8	1.72	10.4	-1.22	W85	8.5×2.5	0
N6517	19.2	6.7	0.60	6.1	-1.34	A90	5.0×2.5	5
N6522	0.9	-3.9	0.25	6.6	-1.44	A90	8.0×7.5	0
N6638	7.9	-7.2	0.23	6.7	-1.15	A90	6.0×2.5	0
N6642	9.8	-6.4	0.21	5.5	-1.30	W85	6.0×2.5	6
M22	9.9	-7.6	0.18	3.2	-1.75	A90	12.5×10.0	10
M4	-9.1	16.0	0.20	2.1	-1.46	A90	10.0×7.5	14
M92	68.3	34.9	0.01	7.7	-2.19	A90	7.5×7.5	0

The IR observing runs are listed in table 1. Table 2 lists some properties of the clusters observed. Column 1 is the cluster identification, columns 2 and 3 give the coordinates of the cluster centers in the Galactic system. Columns 3, 4 and 5 give the reddenings, distances from the Sun in kiloparsecs, and metallicities, respectively, from the compilations of Armandroff (1990) or from Webbink (1985) otherwise. The reddening law adopted gives $E(J - K) = 0.56E(B - V)$, and $A_K = 0.35E(B - V)$. Some of the abundances and reddenings listed by Webbink (1985) are derived from techniques that are fraught with errors. In general, parameters derived from CMDs are much more reliable. However, Webbink (1985) gives the only data available for some of these clusters. Finally, column 6 gives the total size of the mosaic for each cluster, and column 7 indicates the number of spectra (if any) for giants in the cluster. The positions of the observed clusters projected onto the bulge are plotted in figure 1. Note that the sample is incomplete for the southern clusters which cannot be observed from Arizona.

Table 3 lists the tidal radii R_t in arcminutes, and the references for published CMDs for the clusters studied here. The tidal radii are taken from Harris & Racine (1979). When multiple CMDs are found in the literature, only the original CMD and the most recent, highest quality ones are listed. About 1/3 of the clusters in this sample do not have any CMDs published to date. In the future, we will combine the present IR measurements with the published optical photometry listed in table 3 to define better the position of the RGB in the L , T_{eff} plane. More accurate distances will be determined this way for the clusters

Figure 3.1 Map of the clusters observed, projected onto the Galactic bulge. The ellipses have semi-minor axes of 0.5, 1.0, and 1.5 kpc.

with blue or extended horizontal branches (HBs). Also listed in table 3 are data for the bulge population, discussed in section 8.

Notes on some individual clusters:

The clusters HP1, ESO45–SC11, NGC6287, NGC6401, NGC6642, and UKS1 are not listed in the compilation of Armandroff (1989, hereafter A89), which means that there is no reliable CMD published for any of them. Pal6 has an instrumental CMD published by Ortolani (1990). The clusters Pal6, ESO45–SC11, HP1 do not have measured radial velocities either. Note that HP1 was erroneously identified as being the same as ESO45–SC11 by Mallen–Ornellas & Djorgovski (1993). These are two different clusters.

We confirm the identity of ESO45–SC11 as a globular cluster, even though it is a very sparse one. The coordinates listed in Webbink (1985) are precise for this cluster. Note that we have listed this cluster as ESO45 for short in the tables.

The clusters TJ5, TJ15 and TJ16 were not found within 2.5×5.0 arcmin of the coordinates given by Webbink (1985). These objects were classified as potential globular clusters by Terzan & Ju (1980). We note that our photometry in these regions reach $K \sim 16$, from which we conclude that the clusters are fainter than that (unlikely), or that these are not real globular clusters. Using the finding charts given by Terzan & Ju (1980), we find that at the position of TJ15 there is a fuzzy object, with integrated $K \sim 14$, that looks like a nearly edge-on spiral. There are several fuzzy objects in the field of TJ5, that

Table 3.3: DERIVED PARAMETERS FOR THE BULGE

Field	rt	E(J-K)	AJ-K	[Fe/H]b	Re	References
N6144	6.3:	0.20	0.025	-1.62	23.8	Alcaino 1980
ESO45	...	0.17	0.145	-0.29	19.1	
N6235	...	0.19	-0.175	-2.28:	19.3	Liller 1980
N6284	10.0:	0.16	-0.262	...	14.2	
N6287	14.1:	0.28	0.235	-0.55	15.7	
N6293	15.8:	0.21	0.300	-0.42	10.8	Heasley & Janes 1992
N6325	...	0.48	-0.040	-1.64	11.5	Harris 1975
N6333	15.5	0.19	0.190	-0.83	16.2	Heasley & Janes 1992
N6356	8.3:	0.15	0.110	0.01	16.0	Sandage+ 1960, Ortolani+ 1992
HP1	5.0:	0.79	0.075	-0.19	4.0	
N6401	8.9:	0.43	0.030	-0.85	6.7	
PAL6	12.6:	0.81	0.004	0.20	3.3	Ortolani 1991
N6440	7.9:	0.62	0.182	0.57	9.4	Martins+ 1980
UKS1	...	1.72	0.040	...	5.2	
N6517	15.8:	0.60	0.210	-0.29	21.5	Harris 1975
N6522	7.1:	0.25	0.170	-0.59	5.6	Arp 1965, Walker+ 1986
N6638	5.9:	0.23	-0.030	-1.30	13.0	Alcaino 1981
N6642	7.9:	0.21	-0.057	-1.59	13.4	
M22	33.1	0.18	0.260	-0.45	14.7	Arp+ 1959, Cudworth 1986, FCP83
M4	43.7	0.20	...	...	25.0	Eggen 1972, Alcaino+ 1984, FCP83
M92	16.6	0.01	...	...	..	Arp 1955, Stetson+ 1990, FCP83
TER2	...	...	0.150	0.50	..	from Christian \& Friel 1992

resemble faint ellipticals, but the object indicated by Terzan & Ju (1980) could not be identified (it is hard to match optical plates to K images).

Malkan (1981) obtained integrated IR photometry for 2 clusters in our sample: Pal6 and UKS1. The colors are $J-K = 1.52 \pm 0.04$, and 2.26 ± 0.04 , for Pal6 and UKS1, respectively. Malkan (1981) derived the reddenings $E(B-V) = 1.4 \pm 0.1$, and 3.1 ± 0.1 , for Pal6 and UKS1, respectively.

Mallen-Ornellas & Djorgovski (1993) obtained integrated photometry for HP1. They infer $E(B-V) = 2.1 \pm 0.2$ and $(m-M)_0 = 13.7 \pm 1.3$, implying a distance of 5.5 kpc.

NGC6325 has a wide variety of abundances determined, as listed by Shawl & Hesser (1986), ranging from $+0.13$ to -1.44 . Likewise, the range in metallicities published for NGC6144 and NGC6356 range from -0.94 to -1.75 , and from $+0.10$ to -0.77 , respectively. The other cluster of our sample whose published metallicity range spans over a dex is NGC6440, ranging from $+0.33$ to -0.69 .

Pal6 appears to be the most metal rich cluster in our sample. Although the spectra do not have very high S/N, the 3 stars give consistently higher Mg+2Fe strength than those of any other cluster. We adopt a final abundance for this cluster of $[Fe/H] = +0.2 \pm 0.3$, consistent with the value listed by Webbink (1985).

For UKS1 we do not have spectra, therefore it is really impossible to derive an accurate metallicity for it. No accurate metal abundance has been determined for this faint and reddened cluster close to the Galactic center, Webbink (1985) gives $[Fe/H] = -1.22$. We would like to stress that a high metallicity for this

cluster cannot be ruled out at this point. Substantial reddening variations are detected in this field, the NW region appears more obscured than the SE region of the 2.5×8.5 field. Malkan et al. (1980) estimate a reddening $E(B-V) = 1.50$ for this cluster based on integrated near-IR photometry.

The cluster ESO45-SC11 has no published CMD. However, Peterson (1986) quotes unpublished results from Webbink (1981): $V_{HB} = 16.61$, and $E(B-V) = 0.31$.

The recent study of Reed, Hesser & Shawl (1987) found significant differences between their reddening determinations and those compiled by Webbink (1985) for two clusters of our sample: NGC6356 (0.33 vs 0.27), and NGC6287 (0.40 vs 0.51). The cluster NGC6356 is the cluster with the highest Mg_2 index in the sample of Burstein et al. (1983), even more metal rich than M69. NGC6356 is also interesting because it is one of the 3 metal rich clusters in the sample of Armandroff (1988) that has a high z (~ 3 kpc). Van den Bergh (1993) has proposed that NGC6287 is the oldest cluster in the Galaxy. However, the range of metallicities published for this cluster ranges from -1.11 to -2.05 .

3.3. Observations

The IR imaging was done at the Steward Observatory 90" telescope, using a camera equipped with the Nicmos3 256×256 Hg:Cd:Te array. The log of observing runs is listed in table 1. The scale of the present observations was 0.6 arcsec per pixel, giving a total field of view of 2.5×2.5 arcmin for a single frame. The observations for each cluster were accomplished by short integrations (3–15

seconds in K, and 5–30 seconds in J), displacing the telescope in declination by a few tens of arcseconds (typically 20–40). About 10–15 of these single frames were taken, resulting in a combined strip of 2.5×6.6 –10 arcmin per cluster, centered on the cluster itself. This data taking procedure yields a significant background field a few arcminutes away from the cluster, where one can determine accurately the background contribution. From 2 to 4 similar strips were taken per cluster, improving the signal to noise. For the brighter clusters, exposures of different time were taken to recover both the brighter and fainter stars.

The airmasses of observations were between 1.5 and 2.5, due to the low elevation of the clusters as seen from Arizona. Whenever possible, the Elias et al. (1982) standards were taken at the same airmasses as the program objects. Some of the nights only one filter was used, but this is justified since the color dependences are very small.

Figure 2 illustrates the final K mosaics obtained for UKS1 and Pal6, which lie in very crowded and reddened regions, close to the Galactic center.

Some of the clusters were observed with only the K filter, due to weather problems. These are N6528, Ter5, Ter2, and M28; the analysis is deferred until the complementary J photometry is obtained.

3.4. Reductions

We have tried to make this large dataset homogeneous, by employing the same observation technique for all the clusters, and the same reduction procedure. Before adopting a unique reduction procedure, various reduction

Figure 3.2 Final K mosaics for UKS1 (2.5×8.5 arcmin), and Pal6 (2.5×6.6 arcmin), two of the closest clusters to the Galactic center, very reddened and with high density background.

techniques were tried, including different photometry packages and procedures (photometry on individual frames vs mosaic, DAOPHOT *vs* DOPHOT *vs* APPHOT).

The problems with our data are due mostly the high airmasses of observations, variable sky background, and bright standards. The variable background results in different magnitude limits and photometric errors from frame to frame. A typical value for the sky background in K is 6500 counts in a 15 second frame. The sky fluctuates in K by as much as 40 counts from frame to frame, and can have a long term fluctuation of up to 12 counts within a single column (typically consisting of 10–15 frames). The background is much less in J (350 counts in a 15 second frame), but the J frames are more crowded, and the stars in J are intrinsically about 0.7 magnitudes fainter than in K. These competing effects plus our choice of exposure times resulted in frames in both colors reaching about the same limiting magnitude. Each single element of the strip was flattened by the median of the rest of the strip. This yielded a very good flat-field in all cases. The different magnitude limits are homogenized when we make the mosaics. We are sensitive to sky variations on timescales of 10-30 seconds, timescales smaller than that are integrated over. Occasional glitches (sky in one frame much brighter than neighboring frames) were fixed by the medianing process, since the frames were offset by the mode. It is customary to reduce the frames by subtracting a constant for the sky. We have not done that, which facilitates keeping track of the problematic frames, as well as the high and low magnitude limits of each frame. In the few cases where single frames are bad, they have

been discarded. The possible causes for these very high sudden sky enhancement are distant lightning (observations were made during the monsoon season, and although the nights were photometric, distant and unusually bright lightning flashes in the horizon might contribute to the background, since there are several CO and H₂O bands in the 1–2.5 μ m window), or also very bright nearby stars outside of the field, but that produce off-axis reflections withing the optics of the camera and the telescope. This last effect was confirmed when some of the mosaics were extended, these bright stars do not produce much trouble if they are included in the field of view of the array, or if they are more than ~ 30 arcsecs away, but they are most disturbing when they are just outside of the field of view. Whenever possible, we tried to avoid these bright field stars, but some stars that look harmless on the TV screen (blue response) turn out to be very red, with disturbing consequences.

The standards of Elias et al. (1982) are much too bright for this telescope plus camera configuration. Therefore, they had to be defocussed, which might introduce zero point errors making aperture corrections. As a consequence, whenever possible the system has been checked against of the near-IR system of Frogel et al. (1983) for the stars in common in some clusters. This was a small number of stars, since the stars in Frogel et al. are mostly brighter than those here. Since the K observations were taken with a similar filter to that used by Frogel et al., the comparison with the Frogel et al. system is straightforward, and is discussed in the next paragraph. However, in general the stars studied here are much fainter than those observed by Frogel and collaborators, in globular clusters and in the bulge.

In keeping with our attempt of homogenizing the system, we have reduced all the nights assuming the same sky conditions, i.e. allowing only zero point shifts from night to night and from run to run, and not for color or extinctions term variations. This is justified because in the near-IR the extinction terms and color dependences are very small. The small color dependences of the near-IR sky also allowed us to observe only one filter per night, which expedites the observing procedure. Even so, standards in both J and K were observed to check for color terms. Whenever possible also, the clusters were observed at about the same airmass in both J and K.

The bias of the detector is exposure time dependent, therefore dark frames of equal exposure time as the object fields were taken at the beginning and end of the night. These frames both account for bias and dark subtraction. The individual frames were dark subtracted. The bad pixels were accounted for when a final image was computed by doing the proper shifts in δ and filtering the bad pixels. The number of frames in which a typical star appears varies for each cluster, and ranges from 4 to 6 times per column, or a total of 8 to 24 times per cluster. Therefore, some of the fields had a total exposure time of as much as 1.5 minutes in K and 3 minutes in J.

3.5. Photometry

The photometric accuracy varied for the clusters, depending mostly on field star density and cluster concentration. In general, $\sigma_K = 0.03, 0.07, 0.15$ for $K = 10.0, 12.5, 14.5$, respectively. For this work we have chosen to select annuli

where the cluster stars are better measured, excluding the concentrated cores. Corresponding field regions a few arcminutes away from the center of the clusters were also measured to account for background contamination and to compare with the clusters.

The relative scale is on firm footing. The absolute scale (i.e. difference with the Frogel et al. scale) is less reliable, because of the slightly different filter transmission, different observing technique, lack of faint standards, and high airmasses of the present observations. Large differences between the aperture photometry of Frogel & Whitford (1987) and PSF fitting photometry have been found at Baade's window –BW– (DePoy et al. 1993). These differences are such that in the mean, the aperture photometry gives brighter magnitudes, and are explained by the presence of nearby companions that fall within the aperture (DePoy et al. 1993). This is bound to occur because in doing aperture photometry, one usually selects a clean patch of sky (and the highest sky measures are usually discarded due to the assumption that they are contaminated by faint stars), while the object star may have nearby companions falling within the aperture, resulting in a brighter measurement. Note also that Frogel, Whitford & Rich (1984) acknowledge possible errors in K of the order of 0.10 mags for their observations of BW giants due to crowding. Despite these drawbacks, the single channel aperture photometry has the very important advantages that the same procedure is used to define the system, and that it takes careful account of the sky variations in the small timescales.

The photometry was performed on the combined frames. We have used the package DAOPHOT (developed by Stetson 1987) in IRAF to do the photometry;

here we will briefly describe the procedure. First, we run DAOFIND to find all the stars more than 3σ above the background. Then, we run PHOT to do aperture photometry of the stars with a small aperture diameter (typically $1.5 \times \text{FWHM}$ of the stellar image). Then we select bright, isolated stars, to run PSF that builds a point spread function (psf). The building of a psf requires an iterative procedure, in which we first make a preliminary psf, then we use it to subtract the psf star and identify its neighbors, then with SUBSTAR and NSTAR we subtract these neighbors from the original image using the preliminary psf. The cleaned psf stars are now used to construct another psf. This procedure is repeated until the psf looks clean. At the same time, the stars that make the psf are inspected again, and the bad ones are rejected. Typically, only 2 iterations were necessary. Depending on the frames, from 1 to 8 stars were used to construct the final psf. Then we run ALLSTAR to do the psf photometry in the original frame. The resulting image, with all the stars subtracted, is inspected to see whether the stars have been cleanly subtracted, meaning that there are no systematic residuals, positive or negative, in the center or near the edges of the bright and faint stellar images. In general, the subtraction is not satisfactory, and we go back to build another psf. Once we are happy with the psf, we run ALLSTAR, and identify in the subtracted image the stars that were missed by DAOFIND because they were close to a brighter companion. We add these stars, and run PHOT again with the small apertures. Since we have a good psf, we run ALLSTAR again with the new star included. Finally, aperture photometry with PHOT on the frame gives the zero point scale and aperture

corrections. For that we use the psf stars with the neighbors subtracted, and run PHOT with different apertures to construct a curve of growth. This will give the total light of the star included in a very large aperture, from which we can derive an aperture correction to the PSF photometry. For the standards we do only the last step, getting the magnitudes and aperture corrections with PHOT. ALLSTAR is not needed for the standards because there is a single standard per frame, and it is isolated in all cases. The whole procedure is repeated for all filters, and then we match the different filters to get the final magnitudes and colors.

DAOPHOT was run using a single point spread function for the entire image, and on the rare occasions where there was a substantial variation across the frame, the combination of frames was repeated with slightly different shifts to improve the situation. In general this procedure worked, but in some frames the psf was still different in different parts of the master image. However, we made sure in all these cases that the photometric differences constructing different point spread functions were small enough to be unimportant ($\Delta m \leq 0.03$). The photometric accuracy varied for the clusters, depending mostly on field star density and cluster concentration.

At the edges of the mosaics, fewer frames are combined, which means a larger number of bad pixels and a larger photometric scatter. However, the generally less dense stellar background compensated.

The errors produced by DAOPHOT are typically 0.03, 0.07, and 0.15 for $K = 10.0$, 12.5 , and 14.5 . Note that these errors are increased in the cores of

the most concentrated clusters. The errors depend on overall crowding due to background bulge giants, cluster concentration, number of frames per star, and exposure time. For some of the brightest clusters, the giants at the tip of the RGB are saturated in our frames. The number of saturated stars in each mosaic is in general between 0 and 3 (except for the M22 field, where this number is 5 to 7).

Even though the IR frames are much less crowded than optical ones, some of the cluster cores are very crowded even at K. These cores require careful reductions, including background fitting, and we leave this task for the future.

We have carefully checked for vignetting effects that might be present at the 90" telescope. For that, the array was mapped with regularly spaced observations of the standard Elias 19. The integration time was 1 sec, and the number counts are equivalent to a typical $K=11$ star at the Galactic bulge, or about 1 magnitude brighter than a typical bulge HB star. The total number of images of Elias 19 ($K = 7.315$) collected was 10×15 , and no spatial variations were detected to the 5% level in neither the J or K filter. From that we conclude that the 90" + 256×256 camera field of view is not significantly vignetted. These multiple images allowed for a precise determination of the internal photometric errors: $\sigma_J = 0.10$, and $\sigma_K = 0.11$. These are the errors of the aperture photometry, the profile fitting photometry is going to yield slightly better errors.

The seeing in V was always ~ 2 arcsec. Even though the clusters are located in the same region of the sky, different airmasses and temperature variations

cause the PSF to vary slightly from cluster to cluster. These variations range from $\text{FWHM} = 2.3$ to 3.0 for the whole sample, but are constant within a single frame, and even within a single cluster mosaic (column of 10–15 frames taken as the unit image to perform the photometry). These typical sizes for the PSFs mean that we do not have a sampling problem, but we are dealing with big pixels photometry. Otherwise, it does not make sense to do profile fitting photometry (although it has been done, see Davies et al. 1993). Different PSF's have been constructed for some mosaics to evaluate the possible systematic effects depending on the stars used to construct the PSF. The offsets are never larger than 0.03.

3.6. Calibration

The calibration to the standard system was done by observing standard stars from the list of Elias et al. (1982). Typically, 5–8 standards per night were observed over a wide range of airmasses, covering the airmasses of the cluster observations.

In particular, we have several stars in common with FCP and Phillips et al. (1986, hereafter PMSL) in M4, and with FCP in M92. For M4 the differences are:

$$\Delta K_{us-PMSL} = 0.078 \pm 0.045 \ (n = 8)$$

$$\Delta J_{us-PMSL} = -0.091 \pm 0.043 \ (n = 8)$$

$$\Delta K_{us-FCP} = 0.028 \pm 0.030 \ (n = 10)$$

$$\Delta J_{us-FCP} = -0.031 \pm 0.032 \ (n = 10)$$

For M92 the differences are:

$$\Delta K_{us-FCP} = -0.039 \pm 0.073 \ (n = 5)$$

$$\Delta J_{us-FCP} = 0.027 \pm 0.092 \ (n = 5)$$

For M22 the differences are:

$$\Delta K_{us-FCP} = -0.15 \pm 0.11 \ (n = 3)$$

$$\Delta J_{us-FCP} = 0.19 \pm 0.15 \ (n = 4)$$

In summary, the agreement in the absolute zero point and dispersion with other photoelectric systems was found to be less than 0.15 magnitudes in J and K for the clusters M92 and M4. For M22 the differences are larger, possibly due to saturation in the stars used for the comparison.

A comparison with the DAOPHOT measurements of Davidge (1991) in Baade's window yields $\Delta K = -0.05, \sigma = 0.08$, and $\Delta J = -0.02, \sigma = 0.11$, for 47 stars in common brighter than $K = 14$ at BW. For stars fainter than $K = 14$, the scatter increases to $\sigma = 0.22$ magnitudes. The rms scatter is in excellent agreement with the DAOPHOT errors. For $K \leq 14$ we have $\sigma = 0.06$, which combined with the errors of Davidge (1991), accounts for the dispersion. We note that Davidge (1991) referred his photometry to Frogel & Whitford (1987) observations of BW giants, so that photometry is not independently calibrated via Elias et al. (1982) standards.

Other comparisons between the single channel aperture photometry of Frogel and collaborators and more recent PSF fitting photometry have been made by Davies et al. (1993), Davidge (1991), and Davidge et al. (1991). In general, the scatter reaches 0.10 magnitudes for all these works, and possible systematic zero point errors of the order of ~ 0.10 mags might also be present. The source of these differences is not clear, but it is possible that all the reasons enumerated in the previous section contribute to the problem. Therefore, we conclude that the present magnitudes and colors are not free from systematic errors, but these data are of comparable quality to those previously cited.

As further check on the photometry, we have obtained photometry of the BW field following 3 different procedures. First, we run DAOPHOT on a frame by frame basis. For that, the bad pixels have to be masked, by interpolating the nearest pixels. A PSF was constructed for each single image. Then, we matched all the stars that were present in different frames, and computed the mean offset and dispersion. Small offsets between frames were obtained, always ≤ 0.10 magnitudes. These offsets were corrected. The explanation is not clear to us, but it may have to do with variable sky transparency in short timescales. This procedure yields the most accurate photometry for a single star. The problem with this is that only a fraction of the field is covered by 8 frames (about 1/2 of it), so that the photometry is not so deep.

Second, we took the original data frames, uncorrected for bad pixels, shifted them accordingly, and combined them by using an average in sets of 4, rejecting the pixels with 3 sigma higher or lower. This procedure fixes the bad pixels. We

had to combine not less than 4 frames, otherwise the combined frame would be too small, and it would be difficult to find good PSF stars. Then, DAOPHOT was run on each of these frames, constructing a PSF for each frame. The mean offsets between frames was negligible here.

Finally, the frames within a column were combined. Then, DAOPHOT was run on every column. A single PSF was constructed for the whole column, using several stars (unlike in the two previous procedures where not many PSF stars were available). The PSF may vary across a column, because of the finite size of the pixels and the different shifts from frame to frame. This will increase the errors in the photometry, however, by a small amount. There were no zero point offsets between columns here. All the 3 photometric reduction procedures were repeated for both J and K frames. The dispersions in J were slightly bigger (in general, $\sigma_J = 1.25\sigma_K$ for our typical exposure times), due to the fact that the different frames do not overlap by as much as in K. This was in part compensated by the reduced background in J.

To summarize, different avenues for obtaining the photometry were explored, and they yield similar results. The rest of the data was processed according to the third recipe described above.

3.7. The Color–Magnitude Diagrams

Figure 3 shows the IR CMDs for the clusters in our samples, along with their background fields. The left panels show the CMD in an annulus where the cluster giants dominate, and the right panels show regions where the field

Figure 3.3 Near IR color-magnitude diagrams for the globular clusters and their respective background fields.

Figure 3 (cont.)

Figure 3 (cont.)

Figure 3 (cont.)

Figure 3 (cont.)

dominates. In general, the mosaics are smaller or of the order of the tidal radii of the clusters (listed in table 3), so the presence of cluster stars even in the extremes of the mosaics cannot be ruled out. However, the background density is high enough that it is relatively easy to select regions where the field outnumbers the cluster stars, and viceversa.

The color dispersion in the bulge population is clearly seen. This is mostly due to metallicity spread, and not to line of sight depth effects (because the RGB in the IR is nearly vertical), nor to differential reddening (because the fields covered are not large enough, and the clusters themselves have very tight RGBs). The exception is UKS1, where substantial differential reddening is detected. In most cases, the dispersion in color for the RGB of a single cluster at about 1 mag above the HB is $\sigma_{J-K} \approx 0.1 - 0.2$ mags, while for the bulge giant branch $\sigma_{J-K} \approx 0.35$ at the same luminosity. This dispersion does not decrease substantially with distance from the Galactic center, rather the mean position of the bulge RGB varies.

Located at different latitudes and longitudes, the clusters sample a wide variety of fields. The fields of NGC6144 and ESO45-SC11 are located outside of the COBE bulge, and can be taken as halo-dominated fields. The field of NGC6517 is also outside of the bulge seen by COBE, and can be taken as a pure disk field. Conversely, the fields of NGC6638, NGC6293 and NGC 6325 are bulge dominated. In the fields of HP1, Pal6 and UKS1 both the disk and bulge contribute to the background significantly. From optical photometry, Ortolani et al. (1993) confirm that the bulge population extends at least to $l = 13^\circ$ along the major axis of the Galaxy.

Unfortunately, the mosaics for the clusters NGC6333 and NGC6287 are not extended enough to contain a pure sample of background bulge population. The sizes of these clusters are big enough that almost all the observed stars belong to them.

The fiducial lines for the RGB of the clusters are also shown in figure 4, after correcting for the (sometimes sometimes uncertain) reddenings and distances listed in table 2. This diagram is dominated by reddening, as can be seen from the position of the well studied clusters M4 and M92. The fiducial lines for the standard clusters M92, M3 and 47 Tuc from Frogel et al (1983) are also drawn for reference. This diagram permits the ranking of the clusters according to metallicity, assuming the adopted reddenings and distances are correct. As argued later, it is not sensible to put the open cluster M67 as a reference in this diagram for the study of globular cluster or bulge giants. Note that in the near-IR CMD the cluster RGBs are almost vertical. So, the influence of distance errors is minimal when trying to rank the clusters according to $[Fe/H]$. On the other hand, the reddening errors are more important.

Adopting $[Fe/H]_{UKS1} = -1.22$, we derive $E(B-V) = 1.50$ for this cluster. For the metal rich clusters Pal6 and HP1 we prefer the values: $E(B-V)_{Pal6} = 1.25$, $[Fe/H]_{Pal6} = +0.2$, and $E(B-V)_{HP1} = 1.25$, $[Fe/H]_{HP1} = -0.5$. For the intermediate metallicity clusters NGC6284, NGC6325 and ESO45-SC11 we favor $E(B-V) = 0.40$, 0.68 , and 0.70 , respectively, adopting the metallicities listed in table 2.

The disk main sequence is clearly seen in the left CMD of UKS1, and to lesser extent also in Pal6, HP1 and N6517, in the stars blueward of the cluster

Figure 3.4 Fiducial RGB lines for the clusters as they appear in the near-IR CMD, after correcting for the (sometimes incorrect) reddening and distances listed in table 2.

RGB. Frogel & Whitford (1987, their figure 2) illustrate the clear separation in the near-IR between the field dwarfs and giants. The dwarf sequence is ~ 0.2 mags bluer than the giant sequence, for the whole range of temperatures considered. In particular, the dwarfs colors rarely exceed $(J-K)_0 = 1.0$.

3.8. The Bulge Population

Now we will compare the globular and bulge giants on a field by field basis. For the study of the bulge population, the presence of a globular cluster in the field is a great advantage. If the metal abundance, reddening and distance of the globular are known, then one can assume that the reddening within a few arcminutes of the cluster is the same, and obtain a mean abundance for the bulge giants in the field. At the same time, the range of abundances can be determined using the intrinsic width of the giant branches of both the globular and the bulge population.

Following that procedure, it is found that within about 500 parsecs of the Galactic center, the bulge giant branch has, within the uncertainties, the same mean color as the metal rich clusters Pal6 and HP1. In the same fields, clearly the bulge giants are redder in the mean than the metal poor cluster NGC6522. Outside 1.5 kpc from the Galactic center, the mean color of the bulge giants resembles more that of the intermediate metallicity clusters ESO45-SC11, M4, and N6517. As the fields studied here do not penetrate far out into the halo, the background giant stars are never as metal poor as M92, M22 or N6293. The range of Galactocentric distances studied here is 3 kpc. Over this range, the

bulge giant branch shifts in color, getting bluer away from the Galactic center (c.f. figure 6). This is consistent with the existence of a metallicity gradient found in optical studies. Terndrup (1988), and Tyson (1991) find a gradient of ~ 0.8 dex kpc^{-1} along the minor axis. Frogel et al (1990) discuss the color gradient in the IR. Their figure 1 shows a gradient in the integrated colors of several fields along the Galactic minor axis. Their figure 2 shows the CMDs for the M giants in these fields. Their IR data are not consistent with the optical data, which shows a steeper gradient (c.f. Frogel 1990). The question left open from the study of Frogel et al. (1990) is that if the gradient seen is reflected for the bulk of the population, of which K giants are more representative. We obtain an affirmative answer for that question. The gradient is real, and not only present in the M giants.

Is the abundance gradient due to the interplay of the different Galactic components, i.e. different relative numbers of halo to bulge stars in these fields? It is unlikely that this is the only cause. Surely different relative contributions of halo stars will drive the mean abundance to higher or lower values, but the fact that both the bulge and the halo have similar *mean* density laws $\rho \propto r^{-3.5}$ (e.g. Terndrup 1988, Rich 1990), implies that the relative total numbers of these components would not vary a lot with distance. In the following chapters we will find from metallicities and kinematics that the halo stars account for 15–25% of the total spectroscopic samples in the different fields, ranging from 0.5 to 2 kpc.

The present study suffers less from the problem of reddening, which caused the biggest uncertainties in the optical determinations. The reddening problem

is alleviated here due to the reduced reddening sensitivity of the near-IR colors, and to the large number of fields studied. These effects are consistent with the findings of Frogel et al. (1990), who study M giants for different fields along the minor axis. The present photometry includes all the giants, but we sample further down the RGB than FCP, avoiding the brightest giants, which are likely to be variable.

We will now determine mean abundances for the bulge at different distances from the Galactic center. The fact that there is a cluster in the field makes this determination much easier. We use the relative differences in color between the mean location of the cluster RGB and the bulge RGB at each field, which can be measured accurate to 0.05 mags. These differences $\Delta(J-K)$ are measured from the CMDs of figure 3. These $\Delta(J-K)$ values have to be corrected by the different relative distances between the bulge and the clusters. All the giant branches are then shifted to the distance of the Galactic center, assumed to be 8 kpc. The distance effects in the colors are computed from the distances of table 2, assuming a slope for the RGB $\Delta K/\Delta(J-K) \approx 14.2$, independent of the metal abundance of the cluster. The distance correction is not critical because the RGBs in the near-IR are almost vertical.

Even though the age of the bulge is uncertain, a difference in age between the field and the globulars will not have a major effect in the metallicities. For example, according to the IR isochrones of Bell (1992), the difference in RGB color for a range in ages from 8 to 18 Gyr is $\Delta J - K = 0.035$, for a cluster with $[\text{Fe}/\text{H}] = -0.7$.

To summarize, we determine the mean metal abundances for the underlying bulge population based on 2 key assumptions: 1) that the reddening is the same within a few arcmin of the cluster, 2) the cluster metallicities are accurate, and 3) the ages of the field and the clusters do not differ by more than ~ 6 Gyr.

Now we have to adopt a J-K vs [Fe/H] calibration. The models, although much improved and complex, might still miss some sources of opacity. However, they can still be accurate in a relative sense, provided careful comparison with the observations of standard clusters is given. Bell (1992) demonstrated that the Bergbusch & Vandenberg (1991) isochrones translated to the near-IR fit extremely well the RGB of 47Tuc down to the TO, including the HB locus. The reddest giants of 47Tuc are M giants. Then, the models of Bessell et al. (1987, 1991) with $\log Z/Z_{\odot} = 0.06$ should fit the locus of the 47 Tuc RGB. Note that we have extrapolated the $1 M_{\odot}$ models to a mass of $0.85 M_{\odot}$ appropriate for 47Tuc (a shift of only $\Delta(J - K) = 0.02$). This extrapolation from the lowest Bessell et al. models is small enough to guarantee no problems. After that, a small shift of 0.05 mags is still needed to bring the models onto agreement with the RGB of 47Tuc. this small shift is no surprise given the different atmospheres used. The Bergbusch & Vandenberg (1991) models assume enhanced oxygen, but with ratios [O/Fe] that decrease with increasing [Fe/H], such that at the metallicity of 47Tuc, [O/Fe] = 0.2. There is then no element/iron ratio conflict when matching this set of isochrones to that of Bessell et al. (1987, 1991).

Having the Bell (1992) and the Bessell et al. (1987, 1991) models into the same system, we can calibrate colors vs metallicity for the whole range covered,

from $[\text{Fe}/\text{H}] = -2.3$ to 0.5 . Following FCP, we calculate the J-K color of the RGB stars at $K = -5$. The slopes $\Delta(\text{J-K})/\Delta[\text{Fe}/\text{H}]$ for the Bell (1992) and the Bessell et al. (1987, 1991) models are 0.20 and 0.23, respectively. We will adopt the following calibration:

$$[\text{Fe}/\text{H}] = 5.0(J - K) - 5.60 \quad (1)$$

where (J-K) is measured at $M_K = -5.5$, which at the distance of the bulge (assumed to be 8.0 kpc) is $K = 9.02$.

This slope is also consistent with ridge lines for the RGBs of the clusters M92, M3, and 47 Tuc used by Frogel & Whitford (1987). Note that FCP give a slightly different slope of $\Delta(\text{J-K})/\Delta[\text{Fe}/\text{H}] = 0.16$. The FCP calibration was reexamined by Brodie & Huchra (1990), who find a slope of 0.18. The integrated J-K colors of globulars follow a similar relationship with slope 0.18 (Aaronson & Malkan unpublished, Silva & Elston 1993). Furthermore, we assume that this relationship holds even for giants over the whole $[\text{Fe}/\text{H}]$ range. Then, an error of 0.05 mags in the measurement of $\Delta(\text{J-K})$ translates in an error for the metallicity of 0.25 dex. The mean abundance of the bulge RGB for each field is then computed as $\langle [\text{Fe}/\text{H}]_{\text{bulge}} \rangle = [\text{Fe}/\text{H}]_{\text{cluster}} + 5 \Delta(\text{J-K})$. This is essentially the same relation (1), but where the zero point in each field is adjusted to the metallicity of the globular cluster of that field. Hence, these abundances are relative, as is the measure of the color difference between the cluster and the bulge RGBs. The measured values of $\Delta(\text{J-K})$ corrected for the distance effect are listed in table 3, along with the computed mean abundances for bulge giants.

Figure 5 (left panel) shows the run of mean abundance *vs* distance from the Galactic center. This Galactocentric distance is corrected for the flattening of the bulge assuming a major to minor axes ratio of 0.7 (e.g. Kent 1992), and it is given in degrees. Then, $R_e = (l^2 + 2.04b^2)^{1/2}$. The right panel of figure 5 is the dependence of the mean field abundance on Galactic latitude. The error bars are the combination of the Δ (J-K) error and the estimated error in the metallicity of the globulars (~ 0.2 dex). The metallicities adopted for the clusters with spectra are those derived in section 10, and not the ones listed in table 2. The field of the clusters UKS1, and N6284 were not considered. The reddening of UKS1 is uncertain and variable, thus so are its metallicity and its distance. The field of N6284 is not well defined, there is a low density of field giants, and the cluster giants are very numerous within the whole mosaic, making it difficult to decide the mean location of the pure bulge/halo RGB. The same problem exists for the field of NGC6325, the uncertain value of the mean bulge abundance in this field is noted with a colon in figure 5 and table 3. Also plotted in figure 5 are the mean abundances found by Terndrup (1988) in 4 fields along the Galactic minor axis, shifted to match $[\text{Fe}/\text{H}] = -0.25$ at Baade's window from McWilliam & Rich (1993).

There are some caveats to figure 5. First, the fields considered have different contributions from the halo, bulge and disk components of the Milky Way. Therefore, the mean abundance plotted in figure 5 is the mean abundance of the background field population. The scatter seen is not due to measurement errors only, but also to the relative contributions of the different components.

Figure 3.5 a) Mean abundances for background giants in the fields of the globulars studied *vs* distance from the Galactic center R_e (accounting for the flattening of the bulge). These mean abundances were derived by differential analysis of the J–K colors as discussed in the text. The error bars indicate our 1σ estimate of the mean abundance. As discussed in the text, the systematic effect of including cluster stars in the field samples would have shifted most of the points downwards by up to 0.2 dex. b) Same as a) *vs* Galactic latitude.

However, in most fields the bulge giants dominate. Therefore, even if there are contaminant populations, the trend is real. Unfortunately, we lack H photometry to produce near-IR color-color diagrams, the addition of these data in the future will be most helpful.

Second, these abundances are relative to the globulars, and are therefore tied to the globular cluster system of abundances. However, the presence of cluster stars in the fields selected to measure mostly bulge giants will bias the measurement of the mean color of the bulge RGB, and therefore its metallicity too. This effect is such that at each field, the mean bulge abundance will be driven towards the mean cluster abundance. Since in almost every field the bulge RGB is redder than the globular RGB, the mean metallicities for the bulge fields will be underestimated (i.e. the measured value of $[\text{Fe}/\text{H}]$ will be smaller than the real mean bulge abundance). That would cause all the points in figure 5 to shift upwards. The size of this effect is estimated to be small (not more than 0.2 dex).

The present approach of comparing locally the position of the RGB of clusters with known abundances and reddenings with the position of the bulge RGB is another step toward putting everything onto the same system. We find that in the inner bulge the RGB matches the locus of Pal6 giants very closely; this cluster is substantially more metal rich than 47Tuc. At the same time, the abundances derived by comparison to the globulars are not as extreme as those found by Rich (1988). We acknowledge that the errors involved are large, and there is no substitute for spectroscopy for determining metallicities. These

conclusions are based on the comparison to the well studied clusters (e.g. we excluded UKS1).

The similarity of the bulge population to that of the most metal rich globulars is not new. The high quality optical CMD's of Ortolani et al. (1990, 1991, 1992) revealed a strong resemblance between the bulge giant branches in BW and Sgr1 (see also Udalski et al. 1993), and those of the metal rich globulars N6528, N6553, Ter1, and N6356. In particular, Ortolani et al. (1993) find $[M/H] \geq 0.5$ for Ter1. They also find that the morphology of the RGB of Ter1 implies higher metal abundance than the bulge population at BW. This implies that metal rich globulars can be used for the determination of metallicities of bulge giants without the need of extrapolating the scale. The bulge field population at BW resembles closely the CMD of NGC6553, a cluster with Solar metallicity according to Barbuy et al. (1992).

Frogel et al. (1990) conclude that the intra-window metallicity dispersion observed in the optical by Terndrup (1989) and more recently by Tyson (1992) is not seen in the IR data. They also conclude that J-K becomes bluer with decreasing latitude, i.e. with increasing metallicity. These 2 conclusions are not supported by the present dataset, where we concentrate on relative abundance determinations, which should be more accurate. For example, binning the data of figure 6 according to Galactic latitude into 3 regions, the mean abundances are: $[Fe/H] = -0.2$ between $b = 0$ and 5 , $[Fe/H] = -0.7$ between $b = 5$ and 10 , and $[Fe/H] = -0.7$ for $b \geq 10$. Part of the reason for this discrepancy is that Frogel et al. (1990) study only bright M giants, while we cover the whole

RGB population down to much fainter levels. Also, the disk contamination is a function of magnitude, the bulge/disk ratio increases with decreasing magnitude (Ruelas-Mayorga & Teague 1992).

The data of Christian & Friel (1992) in the field of Ter2 supports our findings. Their figure 5 shows that the field (mostly bulge) giants are ~ 0.15 magnitudes redder in the mean than the locus of the RGB of Ter2, which is a metal rich cluster, $[\text{Fe}/\text{H}] = -0.25$, according to Armandroff & Zinn (1988). The bulge giants in the field of Ter2 cannot be more reddened than the cluster itself, because this is more distant ($d = 10$ kpc) according to Christian & Friel (1992). Therefore, the bulge RGB at the location of Ter2 appears to be more metal rich than this cluster itself. This cluster has been added to table 3 and figure 5. Independent integrated IR photometry was obtained by Malkan (1981), who gives $J-K = 1.49 \pm 0.04$, and $E(B-V) = 1.3 \pm 0.1$.

3.9. The Blanketing of Metal Rich Giants

Frogel et al. (1984) were the first ones to point out that the location of the BW M giants resembles that of the globular cluster 47Tuc, which is inconsistent with the super-metal rich abundances found by Rich (1988). This has been recently discussed by Davidge (1991), who finds also that the RGB at BW is also ~ 0.3 mags bluer than the locus predicted by the metal rich models of VandenBerg & Laskarides (1987) and Bessell et al. (1989). The colors of Davidge (1991) and Davidge et al. (1992) are not completely independent of those of Frogel et al. (1983), because they used stars measured by Frogel et

al. (1983) as standards. Also, some contamination from the metal poor cluster NGC6522 itself would shift the RGB to the blue. The IR photometry of Ruelas-Mayorga & Teague (1992, their figure 6), shows that the BW RGB is redder in the mean than the RGB of 47Tuc, and than the BW photometry of Frogel & Whitford (1987).

Frogel & Whitford (1987) proposed that blanketing in these super metal rich stars was the cause of the bluer colors. Taylor, Johnson & Joner (1987) argued that the strong blanketing effect seen in BW K giants is due in part to their choice of reddening law, since the effect goes away using a more realistic $E(B-V)/E(J-K)$ ratio. This would not explain away the blanketing in M giants, which is much too strong to be accounted for by a different choice of reddening law. The blue colors of the bulge M giants with respect to field disk M giants are due in part to the different classification schemes used (Terndrup et al. 1991, Ruelas-Mayorga & Teague 1992). Finally, the new high dispersion abundances for the BW giants (McWilliam & Rich 1993) revise the scale of Rich (1988) downwards by $\Delta[Fe/H] \sim -0.3$ dex, alleviating somewhat the problem.

Whatever the source of the mysterious blanketing is, the fact that in the IR the RGBs of the most metal rich globulars and of the bulge have the same mean color, implies that this blanketing is also present in the metal rich globulars. Furthermore, the optical CMDs discussed by Ortolani et al. (1991) for the metal rich clusters NGC6553, NGC6528, and Ter1 show that the RGB is curved, bending over for the reddest giants due to strong blanketing. The same effect is seen in the bulge CMDs at BW and Sgr1, and to a lesser extent in the -8

degree field, by Ortolani & Rich (1993, these CMDs are also shown by Renzini 1993), by Cook (1987), and by Udalski et al. (1993). This suggests that both the optical and near-IR observations are associated, and that the blanketing in the near-IR has the same cause but it is stronger in the optical bands.

The strong blanketing in I with respect to K was discussed by Frogel & Whitford (1987, their appendix A). Note that none of the clusters observed by FCP is so metal rich that the optical RGB bends over for the coolest giants. The most metal rich clusters of their sample are NGC6637 and NGC6553.

The GB (RGB + AGB) is the major contributor to the integrated JK light of these old stellar systems (e.g. Buzzoni 1989, Bruzual 1990). The HB cannot get any redder for such metal rich populations. Therefore, the integrated color of an old stellar population cannot be redder than its GB. This is a crucial point. For example, the most metal rich globular studied by FCP is NGC6553, with $(J-K)_0 = 0.91$. With such a color, it does not follow the relationship adopted for $(J-K)_0$ vs $[Fe/H]$. However, for that cluster, the integrated color is $(J-K)_0 = 0.97$ (Aaronson & Malkan, unpublished). There is a tight correlation between the J-K integrated colors of globular clusters and $[Fe/H]$ (Aaronson & Malkan unpublished, Silva & Elston 1993). It would be surprising if the colors of the RGBs do not follow a similar correlation, since they are the driving factors for the integrated light (Buzzoni 1989, Bruzual 1990). However, it would seem from figure 13 of FCP, that the IR color of the RGB becomes insensitive to $[Fe/H]$ for the most metal rich clusters. If the position of N6553 is redder by ~ 0.10 mags, the relation would be tighter. Note also that the new abundance of Drake et

al. (1992) for M4 shifts this cluster by about 0.4 dex, to $[\text{Fe}/\text{H}] = -1.05$. M4 was one of the discrepant clusters noted by FCP, but this new value (0.25 dex more metal rich than the value adopted by FCP) moves it closer to the mean relation of all the other clusters.

The distance to M69 was revised by Davidge & Martins (1991) and by Ferraro et al. (1993), who find a 0.3 magnitude difference with the previous photographic study. This had also been another cluster that did not follow the J-K vs $[\text{Fe}/\text{H}]$ relationship of FCP.

There is a problem with the integrated colors: Frogel et al (1990, their figure 1) find integrated colors for bulge fields that are ≥ 0.15 mags redder than the most metal rich globulars. The most metal rich globulars measured by Aaronson & Malkan (1981) have $(\text{J}-\text{K})_0 \sim 0.9$. Yet, they argue that the bulge RGB is relatively blue, matching the RGB of the globular cluster 47Tuc.

It is not advisable to use metal rich open clusters as the reference here, like M67 (Frogel & Whitford 1987), to explore what the J-K colors do for higher abundance. This is because none of the opens studied to date show the same CMD morphology (i.e. the bending over of the RGB for the cooler giants) in the optical as the metal rich globulars or the Galactic bulge. There are two important points to consider when comparing the metal rich globulars with the open clusters: 1) the open clusters are not as old as the globulars, and 2) there might be differences in the detailed chemical composition (i.e. $[\text{O}/\text{Fe}]$, $[\alpha/\text{Fe}]$, etc). The enrichment of globulars is mostly due to SNII (e.g. Wheeler, Sneden & Truran 1990), while the opens follow the chemical evolution of the disk, where

SNI are also important (e.g. Edvarsson et al. 1993). The first point is crucial for the study of the bulge: the age of the bulge, although uncertain, is not as young as that of the open clusters, a similarity with the metal rich globulars is more likely. The second point follows also from the discussion of different blanketing present in bulge giants and metal rich globulars. If the source is H_2O , then the $[\text{O}/\text{Fe}]$ abundance differences between the disk opens and globulars can account for the abnormal colors. If the sources is CO, or VO, or TiO, or a combination of any of these molecules, the element/iron ratio will be the determining factor, and in the bulge giants these element/iron ratios are certainly non-solar, and show also a wide range (McWilliam & Rich 1993). It would then not be surprising if the opens and globulars obey different J-K vs $[\text{Fe}/\text{H}]$ relations.

3.10. The Spectroscopy

We obtained spectra for a sample of bright giants selected from the IR photometry in several clusters. In this kind of study, it is desirable to observe giants as close to the cluster center as possible, because of the competing field stars. In this respect, the IR photometry is invaluable, because it allows us to pick giants in highly crowded regions, which is in general not possible with the available optical photometry. The spectroscopic observations and reductions are described in more detail in the previous chapter. The spectra were taken at the MMT with the Red Channel Spectrograph, and at the 90" with the B&C Spectrograph. The slit sizes were 1.5×180 arcsec, and the instrument was rotated to acomodate 2-3 aligned stars at a time. The spectra have 2 Å resolution, and

cover from 4700 to 5400 Å, The strength of several Mg and Fe features defined by Friel (1987) are measured. Each index is the ratio of the flux in a central passband with respect to two continuum passbands on the sides of the spectral feature. In chapter 2 we found that, of all the lines measured, the sum of Mg5175, Fe5270, and Fe5335 is the combination most sensitive to metallicity.

The spectroscopic indices (listed in table 4) were measured after shifting the spectra according to the individual radial velocities. For the spectral indices of the spectra with $S/N \geq 8$, the rms differences between multiple observations are: $\sigma(\text{Mg}) \sim 0.04$, $\sigma(\text{Fe5335}) \sim 0.03$, and $\sigma(\text{Fe5270}) \sim 0.03$. The spectroscopic indices for the different telescopes and instrument setups agree with each other, provided small zero point offsets are applied.

The radial velocities were determined via the cross-correlation technique of Tonry & Davis (1979). These velocity measurements are also described chapter 2. In summary, absolute velocities are good to ≤ 10 km/s, and relative velocities are good to ~ 7 km/s. The internal errors depend on S/N , being ≥ 20 km/s for $S/N \leq 10$.

As argued before, the candidates for the spectroscopy were selected mostly from the IR frames, as close to the cluster center as possible to maximize membership probability. Because these stars are close to the cluster core, the JK photometry is not as accurate as the photometry presented in figure 3 for the different clusters. It is then not surprising that the J-K color spread is a few tenths of magnitude for the member stars with spectra, as seen in figure 5. This fact will not affect our conclusions. For all the stars in common with

Table 3.4 : SPECTROSCOPY

Star	J-K	Vr	Mg	H β	F492	F498	Fe50	Fe52	Fe53	Fe54	Mg1	Mg2	Mgb	MgH
HP1														
b0	0.52	46.2	1.12	0.81	0.83	0.84	0.84	0.82	0.75	0.51	1.08	1.03	0.89	0.99
cen	0.62	63.4	0.90	0.76	0.66	0.99	0.85	0.82	0.82	0.49	0.76	0.83	0.88	0.64
a0	1.07	76.3	0.91	0.83	0.48	0.64	0.78	0.84	0.82	0.53	0.89	0.89	0.86	0.84
c0	0.87	-56.5	1.11	0.85	0.61	0.81	0.83	0.86	0.76	0.58	1.05	1.08	0.98	1.05
d0	0.81	-59.4	0.94	0.83	0.76	0.89	0.83	0.85	0.81	0.54	0.88	0.83	0.89	0.79
cen	0.62	55.1	0.94	0.78	0.71	0.78	0.83	0.86	0.84	0.62	0.82	0.91	0.81	0.69
N6356														
x00	0.89	52.6	1.05	0.82	0.52	0.89	0.82	0.85	0.87	0.64	1.04	0.92	0.97	1.00
115	1.14	54.6	0.96	0.82	0.27	1.25	1.06	0.87	0.79	0.51	1.11	0.81	1.13	1.06
000	0.61	98.6	0.90	0.87	0.68	0.67	0.75	0.81	0.75	0.56	0.70	0.74	0.77	0.49
113	0.66	54.6	0.98	0.88	0.66	0.89	0.79	0.89	0.87	0.65	0.89	0.85	0.92	0.78
111	0.90	36.9	1.05	0.77	0.59	0.79	0.79	0.85	0.78	0.52	0.99	0.97	0.91	1.03
y00	0.81	54.7	0.99	0.79	0.67	0.86	0.82	0.87	0.85	0.65	0.89	0.87	0.88	0.81
104	0.72	87.5	1.00	0.76	0.69	0.79	0.79	0.87	0.83	0.62	0.95	0.84	0.83	0.87
100	0.93	57.2	0.89	0.91	0.66	0.91	0.82	0.87	0.82	0.60	0.78	0.78	0.90	0.72
162	0.35	-94.4	0.75	0.81	0.65	0.79	0.74	0.73	0.70	0.54	0.63	0.70	0.78	0.55
300	0.59	16.6	0.82	0.79	0.76	0.77	0.77	0.82	0.82	0.72	0.71	0.71	0.85	0.74
400	0.58	38.3	0.82	0.81	0.78	0.90	0.81	0.88	0.78	0.58	0.75	0.78	0.92	0.67
500	3.63	55.2	0.88	0.75	0.70	0.85	0.83	0.88	0.88	0.61	0.75	0.71	0.93	0.67
37	0.65	42.5	1.04	0.84	0.25	1.06	1.03	0.80	0.77	0.54	1.15	0.89	1.17	1.13
000	0.59	57.9	0.80	0.79	0.64	0.78	0.79	0.78	0.75	0.45	0.65	0.71	0.78	0.64
80	0.79	67.1	1.14	0.76	0.52	0.91	0.85	0.87	0.88	0.62	1.13	1.07	0.93	1.08
N6401														
b00	0.92	-101.2	0.97	0.84	0.63	0.93	0.82	0.77	0.74	0.56	0.87	0.87	0.88	0.79
a00	1.14	-111.1	0.95	0.78	0.68	0.85	0.79	0.79	0.84	0.66	0.86	0.89	0.84	0.84
c00	0.98	-70.3	0.93	0.78	0.77	0.77	0.77	0.81	0.85	0.61	0.83	0.87	0.73	0.75
400	0.81	-65.8	0.89	0.91	0.70	0.95	0.80	0.82	0.81	0.65	0.82	0.83	0.84	0.78
500	0.92	-14.6	0.93	0.83	0.71	0.84	0.82	0.90	0.91	0.69	0.86	0.85	0.71	0.85
200	0.99	-107.2	0.96	0.84	0.68	0.89	0.80	0.78	0.85	0.68	0.86	0.93	0.85	0.81
300	0.00	-113.5	1.02	0.79	0.55	0.92	0.89	0.74	0.84	0.70	0.99	1.01	0.90	0.94
400	0.00	41.5	0.17	0.88	0.91	0.89	0.74	0.87	0.89	0.59	0.79	0.74	0.84	0.57
g00	0.73	75.0	0.78	0.95	0.74	0.80	0.84	0.83	0.83	0.45	0.68	0.74	0.71	0.77
d00	0.97	-27.4	0.84	0.71	0.56	0.75	0.77	0.76	0.69	0.46	0.72	0.82	0.69	0.64
e00	0.84	-103.6	0.83	0.82	0.71	0.93	0.82	0.79	0.71	0.48	0.73	0.80	0.82	0.68
f00	0.85	-95.6	0.92	0.84	0.70	0.93	0.82	0.72	0.76	0.50	0.79	0.84	0.84	0.64
900	0.00	-54.2	0.75	0.91	0.68	0.60	0.75	0.67	0.67	0.19	0.70	0.72	0.72	0.70
100	0.00	-79.6	1.03	0.60	0.56	0.78	0.77	0.76	0.57	0.41	0.94	0.83	0.97	0.66
N6440														
a00	1.12	-9.6	1.03	0.88	0.31	1.12	0.91	0.86	0.76	0.39	1.01	1.02	0.85	1.12
c00	1.10	-2.7	0.98	0.89	0.01	0.97	0.93	0.93	0.77	0.39	1.20	0.85	1.42	1.23
y00	0.42	-0.9	0.81	0.76	0.59	0.85	0.72	0.80	0.77	0.47	0.67	0.75	0.90	0.56
b00	0.89	-30.1	1.02	0.60	0.63	0.85	0.87	0.86	0.92	0.47	1.05	0.99	1.24	1.00
x00	1.13	28.4	0.92	1.19	0.39	0.75	0.71	0.93	0.63	0.50	0.87	0.99	0.78	0.96
100	0.60	-69.9	0.98	0.74	0.58	1.02	0.83	0.80	0.79	0.32	0.91	0.92	0.89	0.87
cen	0.75	-60.6	0.97	0.85	0.59	0.88	0.82	0.78	0.73	0.36	0.87	0.85	0.88	0.73
300	0.71	-40.3	0.89	0.79	0.54	0.90	0.83	0.81	0.83	0.45	0.77	0.81	0.89	0.67
f00	1.17	12.0	0.94	0.46	0.27	1.23	1.01	0.83	0.75	0.42	1.11	0.92	1.20	1.14
e00	1.30	26.3	1.00	0.88	0.57	1.03	1.05	1.01	0.76	0.41	1.24	0.83	1.50	0.86
d00	1.07	-46.5	1.15	0.72	0.43	0.92	0.77	0.86	0.86	0.45	1.10	1.11	1.29	1.13

Star	J-K	Vr	Mg	H β	F492	F498	Fe50	Fe52	Fe53	Fe54	Mg1	Mg2	Mgb	MgH
Pal6														
b00	1.19	56.4	1.00	0.69	0.58	0.76	0.89	0.92	0.84	0.50	0.91	1.06	0.83	0.88
d00	0.71	201.2	1.15	0.64	0.51	1.88	1.16	0.74	0.85	0.96	0.93	0.95	0.96	0.61
c00	0.67	243.3	1.23	1.02	0.76	1.05	0.86	0.95	0.77	0.46	1.06	0.99	1.14	0.57
f00	0.72	200.0	1.55	0.71	1.87	1.73	0.84	0.84	1.09	0.59	1.51	0.90	1.26	1.91
N6325														
a00	0.92	119.0	1.12	0.80	0.62	0.74	0.78	0.85	0.84	0.78	1.06	1.12	0.83	0.92
cen	0.84	169.1	0.90	0.80	0.71	0.84	0.80	0.81	0.75	0.79	0.80	0.91	0.75	0.75
300	0.00	0.0	0.82	1.11	0.66	0.71	0.72	0.79	0.72	0.79	0.72	0.84	0.75	0.67
400	0.00	-94.2	0.89	0.90	0.72	0.91	0.90	0.80	0.89	0.80	0.84	0.83	0.90	0.56
500	0.00	0.0	0.78	0.90	0.84	0.84	0.83	0.71	0.79	0.81	0.69	0.95	0.74	0.74
N6517														
a00	0.58	-19.0	0.93	0.77	0.72	0.83	0.80	0.82	0.76	0.68	0.81	0.94	0.85	0.74
b00	0.88	42.6	0.90	0.78	0.70	0.88	0.79	0.84	0.78	0.75	0.83	0.95	0.74	0.79
300	0.40	-44.0	0.80	0.78	0.70	0.81	0.77	0.80	0.85	0.80	0.72	0.87	0.75	0.68
400	0.59	91.5	0.79	0.87	0.74	1.03	0.82	0.75	0.76	0.67	0.76	0.74	0.89	0.78
cen	0.34	13.2	0.85	0.84	0.69	0.85	0.78	0.78	0.84	0.77	0.77	0.90	0.79	0.72
000	0.00	-282.3	0.83	0.87	0.66	0.93	0.85	0.82	0.73	0.69	0.75	0.93	0.79	0.70
000	0.00	46.8	0.81	0.81	0.80	0.77	0.64	0.77	0.75	0.82	0.67	0.98	0.65	0.77
N6642														
000	0.00	-126.6	0.95	0.89	0.78	0.84	0.82	0.85	0.83	0.80	0.88	0.90	0.80	0.81
a00	0.92	61.2	0.98	0.78	0.72	0.79	0.80	0.83	0.81	0.86	0.92	0.97	0.85	0.87
b00	0.29	-11.9	0.94	0.94	0.79	0.78	0.79	0.82	0.78	0.77	0.87	0.91	0.75	0.82
300	0.25	99.6	1.04	0.74	0.71	0.84	0.82	0.88	0.77	0.84	0.97	1.02	0.88	0.71
400	0.00	295.1	1.02	0.80	0.70	0.72	0.75	0.77	0.78	0.80	1.00	0.95	0.88	0.83
500	0.00	171.8	0.85	0.75	0.64	0.79	0.78	0.82	0.82	0.79	0.76	0.89	0.76	0.64
600	0.00	59.2	0.86	0.62	0.71	0.83	0.78	0.81	0.75	0.75	0.77	0.90	0.79	0.71
700	0.00	86.9	0.86	0.88	0.73	0.86	0.81	0.81	0.76	0.70	0.81	0.86	0.84	0.72
cen	0.76	37.4	1.05	0.83	0.74	0.85	0.83	0.84	0.76	0.71	0.99	1.05	0.90	0.96
c00	0.92	-69.9	0.71	0.91	0.85	0.76	0.82	0.80	0.75	0.81	0.69	0.44	0.86	0.54
300	0.00	-44.2	0.86	0.87	0.80	0.93	0.81	0.78	0.81	0.79	0.74	0.80	0.80	0.70
400	0.00	45.3	0.77	0.80	0.71	0.85	0.80	0.84	0.79	0.82	0.71	0.71	0.82	0.68
500	0.46	-38.0	0.82	0.99	0.76	0.81	0.81	0.71	0.79	0.77	0.72	0.82	0.77	0.59
600	0.00	103.9	0.69	0.96	0.71	0.87	0.82	0.84	0.71	0.81	0.65	0.67	0.80	0.60
M22														
203	0.85	-183.0	0.85	0.75	0.67	0.83	0.77	0.76	0.77	1.06	0.73	0.76	0.77	0.72
315	1.25	-115.2	0.85	1.01	0.68	0.99	0.83	0.86	0.84	0.95	0.74	0.62	0.86	0.68
510	0.76	-77.1	0.76	0.76	0.70	0.87	0.81	0.81	0.75	1.02	0.64	0.57	0.87	0.64
572	0.25	-112.9	0.75	0.85	0.61	0.80	0.73	0.75	0.69	0.97	0.63	0.66	0.75	0.60
478	0.44	-160.7	0.77	0.82	0.75	0.88	0.79	0.69	0.65	0.98	0.62	0.63	0.74	0.57
053	0.58	-48.3	0.92	0.90	0.68	0.95	0.83	0.82	0.75	0.78	0.88	1.09	0.82	0.69
408	1.01	-160.2	0.85	1.26	1.06	0.79	0.77	0.75	0.66	0.89	0.83	1.16	0.84	0.75
467	1.00	-138.5	0.79	0.85	0.65	0.95	0.80	0.78	0.80	0.75	0.76	1.00	0.79	0.76

Figure 3.6 Spectral indices ($\text{Mg}5175 + \text{Fe}5270 + \text{Fe}5350$) *vs* $(J-K)_0$ for red giant members of the clusters from radial velocities. In the left panel the clusters are: M22 ($\bullet$), M4 ($\circ$), NGC6401 ($\times$), NGC6517 ($\circ$), and NGC6642 ($\blacktriangle$). In the right panel the clusters are: NGC6325 ($\star$), NGC6440 ($\blacksquare$), NGC6356 ($\boxtimes$), Pal6 ($\triangle$), and HP1 ($\square$). The dotted lines represent, from bottom to top, $[\text{Fe}/\text{H}] = -1.75, -1.0$, and 0.0 , respectively.

BV photometry, the agreement between the abundances determined in both the $\text{Mg}+2\text{Fe}$ vs $(\text{B}-\text{V})_0$ and the $\text{Mg}+2\text{Fe}$ vs $(\text{J}-\text{K})_0$ planes is excellent.

Figure 6 shows the spectroscopic index $\text{Mg}5175+\text{Fe}5270+\text{Fe}5335$ vs $(\text{J}-\text{K})_0$ for cluster giants. The left and right panels contain the intermediate and high metallicity clusters, respectively. The fiducial lines are adapted from the $(\text{B}-\text{V})_0$ vs $[\text{Fe}/\text{H}]$ diagram of chapter 2, shifted to match the standard clusters M4 and M22, with $[\text{Fe}/\text{H}] = -1.05$ and -1.75 , respectively. This figure allows us to rank the clusters according to metal abundance. The J-K axis in figure 6 has been dereddened according to the $E(\text{B}-\text{V})$ values from the literature listed in table 2.

All the giants plotted in figure 6 are cluster members according to radial velocities. Although the radial velocities are good only to ≤ 10 km/s, due to the large velocity dispersion of bulge giants, it is easy to discriminate possible cluster non-members. The membership criteria adopted is to retain all the giants with velocities within 2σ of the mean cluster velocity. About 30 % of the giants were discarded as non-members. The percentage of non-members is larger for the clusters closest to the plane and the Galactic center (Pal6, HP1, N6440, N6401), and smaller for the more distant clusters (N6356, N6517, N6325, N6284).

Ultimately, the abundances are derived from an iterative procedure: First we adopt a $E(\text{B}-\text{V})$ value (generally from Webbink (1985)), and make the $\text{Mg}+2\text{Fe}$ vs $(\text{J}-\text{K})_0$ diagram, from which we infer a first value of $[\text{Fe}/\text{H}]$. With that metallicity, we go back to the photometry and derive a new reddening value. Then, with this new $E(\text{B}-\text{V})$ we repeat the previous procedure, as many times

as necessary until the results converge. Our final abundances are accurate only to ~ 0.2 dex, due not only to the uncertainties in reddenings and distances, but also to the scatter in the $\text{Mg}+2\text{Fe}$ indices.

The final adopted values of $E(\text{B}-\text{V})$ and $[\text{Fe}/\text{H}]$ for all the clusters with spectra are given in table 5, after the iterative procedure described above. Columns 2 and 3 give the reddening with its estimated uncertainty. Columns 4 and 5 give the metallicities with the uncertainties. Note that in figure 6 the cluster stars were plotted with the $E(\text{J}-\text{K})$ values from table 2, not with the final values listed in table 5. This is to illustrate that even without the revised reddening values, the clusters reasonably fit the present abundance determinations. The errors were for the reddenings and metallicities were estimated from the scatter of the data points. These results agree with previously published determinations of reddenings and metallicity within the error bars of these several determinations, with a few exceptions.

The cluster Pal6 turns out to be the most metal rich cluster in our sample, with $[\text{Fe}/\text{H}] = 0.2 \pm 0.3$. The indices for the 3 giants considered members show significant scatter. However, these 3 giants in Pal6 have very similar $(\text{J}-\text{K})$ colors, within 0.06 magnitudes. We can add up all these spectra and measure the indices to improve the S/N. The calibration should still work for the combined spectrum, taking a mean $(\text{J}-\text{K})_0 = 0.70$. This procedure yields again $[\text{Fe}/\text{H}]_{\text{Pal6}} = 0.2$.

The cluster NGC6325 is more metal rich than the value listed by A89 by 0.3 dex. It should be noted that only 2 spectra were taken for N6325, and the

Table 3.5: DERIVED CLUSTER PARAMETERS

ID	E(J-K)	sigma	[Fe/H]	sigma
M4	0.20	0.03	-1.05	0.05
M22	0.18	0.03	-1.75	0.15
N6517	0.75	0.15	-1.2	0.20
N6642	0.26	0.05	-1.4	0.20
N6401	0.33	0.05	-1.1	0.20
N6325	0.48	0.05	-0.9	0.30
N6440	0.57	0.05	-0.5	0.20
N6356	0.15	0.03	-0.4	0.20
HP1	0.94	0.10	-0.3	0.20
Pal6	0.91	0.05	0.2	0.30

final metallicity is taken as the mean of both stars (see figure 6). Again, the 2 stars have similar colors, and adding up the spectra yields the same metallicity for the cluster. However, note that our determination is close to the mean of all the published values of $[\text{Fe}/\text{H}]_{\text{N6325}}$ as listed by Hesser & Shawl (1986), while the metallicity of A89 is the lowest of all metallicities published for this cluster.

The metallicity for HP1 is consistent with that of Armandroff & Zinn (1988), confirming that this cluster is not as metal poor as suggested by Webbink (1985) who gives $[\text{Fe}/\text{H}] = -1.68$. We derive a slightly different reddening than that adopted by Armandroff & Zinn (1988).

The reddening of the cluster NGC6401 is higher than the value given by A89 by 0.2 mags. The results listed in figure 6 will be improved with the combination of the optical with the IR photometry, work which is in progress.

It is evident from figure 6 also that the scatter in the spectral indices is much larger for the metal rich clusters ($\sigma_{Mg+2Fe} \approx 0.2$), than for the

intermediate metallicity clusters ($\sigma_{Mg+2Fe} \approx 0.1$). This is also seen in the $Mg+2Fe$ vs (B-V) diagram (shown in chapter 2). This dispersion is much larger than the measurement errors. The scatter within Pal6 giants is very large, but we attribute this to a combination of the measurement error for low S/N spectra plus intrinsic scatter.

As noted in the previous chapter, an increase of the dispersion with increasing [Fe/H] is contrary to expectation, because for more metal rich clusters the lines are stronger, and the measurement of the indices should be more accurate. The scatter is not entirely due to Poisson statistics, because it is persistent even for the higher S/N spectra. It also seems unlikely that it is due to intrinsic variations of chemical composition for the stars within a cluster, because such strong effects are not seen in the well studied clusters 47Tuc and M71, although some minor variations cannot be discarded.

Furthermore, it is not clear whether we are measuring both first ascent RGB or AGB stars. Some of the giants are likely to be on the AGB, with different atmospheric structures and compositions. A variation in gravity may not be enough to account for the differences, but such could be accompanied by slight variations in chemical composition due to mixing. Nonetheless, we conclude that the $Mg+2Fe$ index is still sensitive to metal abundance for the most metal rich globulars, even though the scatter increases.

The fiducial lines are adapted from the (B-V) vs $Mg+2Fe$ diagram, shifted to match the positions of the standard clusters M4 and M22. A similar locus for the lines is obtained applying the transformations of B-V to T_{eff} and J-K

to T_{eff} given by McWilliam (1990). In the region of interest here, from the data presented by McWilliam (1990), we derive the transformation $(B - V)_0 = 1.78(J - K)_0 - 0.18$. This is valid for $0.9 \leq (B - V) \leq 1.65$, and $0.6 \leq (J - K) \leq 1.05$, and the dispersion is ~ 0.1 mags.

3.11. The Brightest Bulge Giants

Inspection of the CMDs presented in figure 3 reveals that the brightest field giants reach in general the same luminosities as the brightest cluster giants. The number of stars missed in each frame due to saturation in the J or K bands are too few to alter this conclusion. This result is in agreement with the early findings of Frogel & Whitford (1987) in their study of the luminosity function at Baade's window. This is also confirmed by our determination of the bulge luminosity function in SgrI, BW, F588, M22 and F589.

In all the fields studied, there is no evidence for the bulge having a substantial high luminosity, intermediate age stellar population, more than that expected for the disk itself. Such bright stars were detected in the Galactic center (Rieke 1987, Haller 1992), the bulge of M31 (Rich & Mould 1991, Mighell & Rich 1993, Rich, Mould & Graham 1993), the bulge of M33 (Minniti, Olszewski & Rieke 1993) and in M32 (Elston & Silva 1992, Freedman 1992). The brightest stars in the bulge fields reach similar luminosities as the brightest globular cluster giants, after accounting for distance differences. The recent results of Glass (1993) in the SgrI field at 300 pc, and of DePoy et al. (1993) in the BW field at 500 pc from the center confirm that the brightest AGB stars do not

exceed $M_{bol} = -5.5$. This is consistent with a similar bulge-cluster population, and also argues for an old bulge, at least as old as the metal rich globulars. So far, very few metal rich globulars have reliable ages determined from deep CCD CMDs: N6553 is 12 Gyr (Ortolani et al. 1991), 47Tuc and M71 are 13 Gyr (Hesser et al. 1987, and Hodder et al. 1992). If indeed the bulge is associated with the metal rich globulars, its age is ≥ 10 Gyr. Such old age is consistent with kinematic information and with rapid enrichment (e.g. Matteucci & Brocato (1990), and supports the idea of formation via dissipational collapse (as we discuss in subsequent chapters).

The bulge lacks a significant intermediate age stellar population compared to the bulge of M31. The detection of intermediate age stars in the bulge of M31 does not mean that the M31 bulge formed ~ 5 Gyr ago; a population as old as that of the globular clusters is too faint to be detected. The bulk of the M31 bulge could still be ~ 10 Gyr old. Note also that the nuclear region of M31 lacks a population as young as seen in the nucleus of our Galaxy, the star formation activity in the central regions of these two similar spirals is very different (Rieke 1987, Haller 1992). In the case of M33, a much smaller spiral with a tiny bulge, Minniti et al. (1992) suggested that the bright bulge stars they find could have resulted from star formation triggered by a recent interaction, consistent with the heavily warped disk. However, they also point out that there could be an underlying, ~ 15 Gyr old bulge population that falls beyond the reach of their photometry. The picture that emerges from the 3 spirals of the Local Group is that the star formation histories in the central regions are different, in which

mergers, interactions and nuclear activity play a key role, and at the same time, they could share a ≥ 15 Gyr old population.

3.12. Summary and Conclusions

We have presented near-IR CMDs for several low latitude, heavily reddened globular clusters. We have defined the location of their RGBs in the K, J-K plane, putting them all together in a uniform system. The position of the RGBs allows us to estimate the metallicity for several clusters with previously unknown or uncertain abundances. The RGB in the JK CMD for the most metal rich globulars does not turn-down as seen in the optical CMDs (Ortolani et al. 1991)

In general, there is good agreement with previous estimates of reddenings and metallicities for most of the clusters. We point out a few discrepant clusters, for which improved values of $E(B-V)$ and $[Fe/H]$ are obtained from the present data.

We have also compared the cluster giants with the field giants in different locations towards the Galactic bulge. Different fields dominated by bulge giants, halo giants or disk giants reveal that the location of the bulge RGB is similar to that of the most metal rich globulars. This result, combined with the fact that the brightest cluster giants reach similar luminosities at K as compared to the bulge giants, leads to our first major conclusion: There is no apparent difference between the bulk of the bulge population and that of the most metal rich globular clusters.

The reddening in the bulge fields is similar to that of the cluster in each single case; strong differential reddening is seen only in the field of UKS1. This

allows a direct comparison between the cluster RGB and the bulge giants to determine metal abundance for the latter.

The population of the inner bulge appears homogeneous, as can be seen in the fields of Pal6, HP1 and NGC6522. Outside of 0.5 kpc there is a gradient in the mean color of the bulge giant branch, getting bluer with distance from the Galactic center. This is a confirmation of the metallicity gradient found in previous optical studies. A crude estimate of the gradient is $\Delta[Fe/H]/\Delta R_{gal} \sim -1$ dex/kpc between 0.5 and 1.5 kpc. This is consistent with previous findings (e.g. Terndrup 1989, Tyson 1991).

In the inner fields, we find considerable more dispersion in J–K than that found at Baade’s window and other inner bulge fields by Frogel, Terndrup & Whitford (1991). Their CMD’s are of the Blanco survey of M giants. The CMD’s of Frogel & Whitford (1987) for K giants at Baade’s window show larger color range, consistent with our results. We do not find significant numbers of very red luminous variables ($J-K \geq 1.5$) like those studied by Glass (1993), although some could have been missed because of saturation effects.

The cluster M4 was found to be anomalously red for $[Fe/H]_{Zinn} = -1.4$ in the study of FCP. We confirm this fact, and agree with FCP that M4 must have a slightly higher metallicity. The recent high dispersion echelle spectra and model atmosphere analysis of Drake et al. (1992) find $[Fe/H] = -1.05 \pm 0.02$ for this cluster. The spectroscopic indices of chapter 2 also agree with this higher value (see chapter 2 and figure 6).

The contribution from the disk itself is significant only within a few degrees from the plane (as seen by the disk MS in the fields of UKS1, Pal6, F589, etc).

From the present photometry, we infer parameters for some poorly studied clusters with errors of 0.10 magnitudes in $E(B-V)$, errors of 0.3 dex in $[Fe/H]$, and errors of 0.2 magnitudes in distances. The reddening, distances and abundances are in good general agreement with previous studies.

The exceptions are NGC6325, for which we find a higher metallicity, $[Fe/H] = -0.9$, and NGC6401, for which we estimate a higher reddening, $E(B-V) = 1.3$. In particular, we confirm the high reddenings found for the cluster UKS1, the most reddened cluster in our sample, with $E(B-V) = 3.1$.

From optical spectra of IR-selected giants we confirm the metal rich nature of N6356, N6440, HP1 and Pal6. Ranking them by the spectroscopic indices, we find that the first three clusters have approximately the same metallicity. Pal6, however, is more metal rich.

The objects TJ5, TJ15, and TJ16 are not detected. It is likely that they are not real globulars.

Finally, table 5 summarizes the results of this paper, where we list the newly derived reddenings, and metallicities, whenever they are different from these listed in table 2.

4. VELOCITIES AND ABUNDANCES FOR BULGE GIANTS IN FIELD F588

We have obtained radial velocities for 319 stars in a bulge field at $l, b = (8, 7)$. For this whole sample we obtain a mean Galactocentric velocity $\langle V \rangle = 54.4 \pm 4.7$ km s⁻¹, and $\sigma = 84.4 \pm 3.3$ km s⁻¹, confirming that the Galactic bulge is flattened by rotation. We derive accurate abundances based on a set of spectral indices calibrated against a grid of ~ 400 standard stars. Dividing the sample according to metallicity, we find that there is a clear kinematic separation between the halo and bulge components. The 65 K giants with $[\text{Fe}/\text{H}] \leq -1$ (mostly halo giants) have $\langle V \rangle = -7.0 \pm 13.6$ km s⁻¹, and $\sigma = 109.4 \pm 9.6$ km s⁻¹. The 31 "pure" halo giants (with $[\text{Fe}/\text{H}] \leq -1.5$) have $\langle V \rangle = -5.8 \pm 20.4$ km s⁻¹, and $\sigma = 113.5 \pm 14.4$ km s⁻¹. The mean Galactocentric velocity and velocity dispersion for 194 bulge K giants (stars with $[\text{Fe}/\text{H}] \geq -1.0$) are $\langle V \rangle = 65.9 \pm 5.1$ km s⁻¹ and $\sigma_V = 71.9 \pm 3.6$ km s⁻¹. The difference between halo and bulge kinematics is of very high statistical significance. The Galactic bulge and halo seem to be distinct components, defined by consistency among $[\text{Fe}/\text{H}]$, $\langle V_r \rangle$, and σ .

The 26 M giants observed in the field have kinematics consistent with their being bulge members, although not very metal rich. The 13 giants brighter than the bulge giant branch tip ($R \leq 15$) show halo-thick disk kinematics.

For the bulge K giants there is a trend for the more metal poor stars to have larger σ and smaller rotation velocity. Given the size of our sample, this trend is statistically significant. These findings are consistent with a dissipational

collapse scenario of bulge formation, where the degree of rotational support is expected to increase with increasing metallicity.

The dependence of velocity dispersion on distance from the Galactic center is determined by combining our data with existing data at Baade's window. For a power law dependence of velocity dispersion with distance $\sigma \sim r^{-m}$, it is found that $m = 0.35$ and 0.00 ± 0.05 for the bulge and halo, respectively. While the line of sight velocity dispersion of the bulge giants decreases steeply with distance from the Galactic center, the line of sight velocity dispersion for the halo decreases very slowly if at all.

The dependence of kinematics on metallicity presented here also help to explain differences between the scale-lengths of the bulge determined from integrated light in the optical and near IR, and from other bulge tracers.

4.1. Introduction

Freeman (1987) pointed out that little is known about the rotation of the metal weak component in the inner part of the Galaxy, at radii comparable to those at which bulge rotation is observed in other galaxies. Our own Galaxy is the best place to try to separate the bulge and halo components in these inner regions.

Minniti et al. (1992) found that the Galactic bulge is rotating, like the bulges of other similar galaxies. We also found that the velocity dispersion decreases with increasing Galactocentric distance. This is surprising, since the halo itself is approximately isothermal, with velocity dispersion constant over

a large range of Galactocentric distances (Norris 1987). However, the halo kinematics in the inner regions of the Galaxy are not known. The halo is present there, it is certainly not going to disappear, but whether it is similar to the local halo, or changes inside the inner few kpc is not known.

In the bulge, there has also been a trend for the metal rich stars to be more rotationally supported than the metal poor stars (Minniti et al. 1991, see also Rich 1990), but that trend was not highly significant according to statistical tests. In particular, if these trends were real, it is not proven yet that they are due to a population transition (e.g. between the disk, halo and bulge, or thick disk and bulge), or that they are intrinsic to the bulge.

However, such trends are the most important signatures to test different scenarios of bulge formation. Note that the abundance gradient present in the bulge (Terndrup 1988, Rich 1990) could be interpreted as the signature of dissipational collapse, and should be accompanied by a kinematic imprint.

To solve the problem one needs a large data set, detailed modeling and realistic account of contamination by the other Galactic components, namely the Halo and Disk. A large data set will provide not only with better values for V_{rot} and σ , but also with detailed velocity distributions that can be modeled via Galaxy models and Monte-Carlo simulations.

The two most important questions we would like to answer on the Galactic bulge research are: What is the age of the Galactic bulge? and How did the bulge form? This report attacks the second question, by studying the kinematics of bulge giants of different metallicities.

During a dissipative collapse, metallicity gradients are generated by the settling of enriched material towards the center, and also towards the equatorial plane in a rotating system (Larson 1976, see also Larson 1992). In such a scenario, age, metallicity and kinematics are correlated. If the bulge formed by a uniform dissipational collapse from the leftover material of the halo, then we should explore these correlations.

Before embarking on a project like this, consideration of the size of the samples needed to answer different questions is important. To determine the rotation and velocity dispersions to about 10 and 8 %, respectively, from medium resolution spectra, the number of bulge giants required is about 60 per field. To determine if there is a significant trend of kinematics with metallicity, one needs that number of stars per metallicity bin, then a total sample of about 200–300 giants per field will suffice. Note that for off axis fields, it would be easier to identify different Galactic components based on kinematics, because of the added help of the mean rotation velocities. Similarly, a few hundred giants per field should be enough to study the shape of the velocity distribution of the bulge, to search for departures from gaussian behavior or the presence of different kinematic populations. Much larger sample sizes are not likely to produce different results and are not a justified use of telescope time. Clearly, the energy for bulge research should be directed to other pieces of information to add to the radial velocities, such as the measurement of detailed chemical abundances, and proper motions.

The dependence of kinematics on metallicity was discussed previously by Rich (1990), and Minniti et al. (1991). They find trends for the velocity

dispersions to be larger for the metal poor stars with respect to the more metal rich ones, even though these authors point out that the sizes of the samples are too small to draw any strong conclusions from those data. There are some unanswered questions with these previous data.

For example, Minniti et al. (1991) did not account for halo stars in their sample.

Also, Rich (1990) points out that the metal poor stars (with $-0.9 \leq [Fe/H] \leq -0.3$) at Baade's window have halo kinematics. However, these stars were more metal rich than what we know as halo. These stars now turn out to be more metal poor according to the new abundance scale of McWilliam & Rich (1993). If we call halo giants those with $[Fe/H] \leq -1.0$, then up to 12 metal poor stars in the Rich (1990) sample could be halo stars. Note that in the McWilliam & Rich 1993 sample, the lowest metallicity stars might belong to the halo rather than the bulge also on the basis of chemical composition. Their 3 stars with $[Fe/H] \sim -1$ have higher Si and Ca than all the other more metal rich stars, consistent with normal halo composition, although the Mg and Ti abundances are uniform for the whole sample.

Also, Rich (1990) reanalyzes the Mould (1983) sample of Baade's window M giants, finding a trend for the hotter, more metal poor M giants to have larger σ than the cooler, more metal rich ones. This effect is not confirmed by the much larger data set of Sharpless et al. (1991).

Finally, the recent study of Morrison & Harding (1993) on a field at 2 kpc from the Galactic center show distinct kinematics for the metal poor stars (which

they associate with the halo) and the metal rich stars (which they associate with the bulge). However, their field lies outside of the main bulge as outlined by IRAS and COBE, where the super metal rich bulge stars (for example the progenitors of OH/IR stars) are not represented. This is indeed confirmed by Morrison & Harding (1993) metallicity distribution, where they find no stars with $[\text{Fe}/\text{H}] \geq 0$. It is then not clear how to compare this field to Baade's window, fields at intermediate distances, well within the bulge, are needed.

Since the halo is kinematically hot, its influence is going to be very significant in samples of giants towards the bulge, even if the halo stars are few compared to bulge stars. It is reasonable to expect then that some of these V, σ vs $[\text{Fe}/\text{H}]$ trends observed by Minniti et al. (1991) could be due in part by halo contamination of the bulge samples. Thus, the reality of any kinematic dependence on metal abundance remains to be settled, by means of a clean sample of bulge stars. The present study improves the situation by increasing the Minniti et al. (1991) sample by a factor of 4, and by taking careful account of the halo star contamination.

The field studied here, referred to as F588 after the ESO plate number, has been identified as a clear window toward the bulge on the basis of visual inspection of the Kyoto $\text{H}\alpha$ survey, the IRAS survey and SRC Southern Sky survey (B, R and I plates). The center of the field is located at $\alpha, \delta = (17:40, -18:10)$, or $l, b = (8, 7)$, at a radial distance from the Galactic center of 1.48 kpc for $R_0 = 8$ kpc. The field appear as a uniform region with high stellar density over a radius of about a degree, and with no obvious dust lanes. The mean

reddening is estimated to be $E(B-V) = 0.18$ from the multicolor photometry. One of the advantages of this field is that it is accessible from observatories in the Northern hemisphere. The IRAS and COBE infrared images revealed a boxy Milky Way bulge. Field F588 is located in one of the corners of the box. The satellite pictures prove that in this field disk emission is minimal with respect to the bulge.

This paper is organized in the as follows: section 2 presents the photometry, selection, section 3 discusses the spectroscopy, section 4 describes the data reduction, section 5 gives the velocity determinations, section 6 presents the abundance determinations. In section 7 we summarize the whole data set, section 8 discusses the metallicity distribution in this field, section 9 presents the dependences of kinematics on metal abundance for the giants observed. Sections 10, 11 and 12 analyze the contamination from the halo, thick disk and thin disk, respectively. Section 13 discusses an application of the Boltzmann equation to our data. The kinematics of the M giants are presented in section 14. Finally, section 15 gives a summary and the conclusions.

4.2. The Photometry

Photographic photometry in the B_JRI bands of plates of the UKST survey was obtained with the APM machine by M. Irwin, using the standard APM procedure and internal calibrations. It is important to note that the photographic sample is not complete: only the non contaminated stars present in all 3 color plates, with very strict roundness parameters are considered.

However, we are complete enough for the purposes of this study, sampling uniformly the whole range of bright bulge giant candidates. The transformation to the standard Johnson B, Cousins R and I systems was performed via CCD observations obtained at the 90" telescope of Steward Observatory during 2 runs. The first run was in June 1989 by R. Cutri, who kindly provided us with BRI frames of F588 taken with the 800×800 TI CCD chip. This data are good, but it was found that only a few stars with APM photometry fall within the 2.5×2.5 arcmin covered by that chip. Then, a second run with the 2048x2048 Loral CCD chip on 12 July 1992 provided with larger area coverage for the BRI frames from which about 20 stars are in common with the APM photometry. We followed the standard CCD reduction procedures within the IRAF packages. The photometry was obtained with the DAOPHOT package also in IRAF. The equations to transform to the standard system are for the Loral run:

$$B = b - 0.25 X + 0.15(b - r) - 2.19$$

$$R = r - 0.09 X + 0.02(b - r) - 0.97$$

$$I = i - 0.09 X + 0.04(b - r) - 1.82$$

where X is the airmass (~ 1.55), and b, r, i are the instrumental magnitudes. These equations include the aperture corrections ($\sim 0.2 - 0.3$ mags). The B magnitudes of 5 Landolt (1992) standards are recovered with $\sigma_B = 0.03$. The R magnitudes of 4 Landolt (1992) standards are recovered with $\sigma_R = 0.025$. The I magnitudes of 9 Landolt (1992) standards are recovered with $\sigma_I = 0.01$. The

errors produced by DAOPHOT are typically 0.01, 0.02, and 0.03 for $R = 17.0$, 18.5, and 20.0, respectively. The other filters gave similar errors.

The equations to transform to the standard system are for the TI run:

$$B = b - 0.25 X + 0.04(b - r) - 1.73$$

$$R = r - 0.09 X - 2.68$$

$$I = i - 0.09 X + 0.02(b - r) - 2.88$$

These equations include the aperture corrections ($\sim 0.2 - 0.3$ mags). The B magnitudes of 5 Landolt (1992) standards are recovered with $\sigma_B = 0.05$. The R magnitudes of 5 Landolt (1992) standards are recovered with $\sigma_R = 0.03$. The I magnitudes of 5 Landolt (1992) standards are recovered with $\sigma_I = 0.03$.

The differences in the photometry between these 2 runs are: $\Delta R = 0.03 \pm 0.02$ for $R \leq 15.4$, $\Delta B = -0.02 \pm 0.02$ for $R \leq 16.1$, and $\Delta I = 0.00 \pm 0.01$ for $R \leq 14.5$, in the sense Loral minus TI CCD magnitudes.

The transformation between APM and CCD systems was found to be linear:

$$R = R_{APM} - 2.31$$

$$B = B_{APM} + 0.23(B - R)_{APM} - 1.75$$

$$I = I_{APM} - 2.02$$

These relations are based on 17 stars in common between the CCD and APM photometry. These stars cover a wide range in colors, but a limited range in magnitudes ($R = 12.3$ to 14.7). Stars brighter than 12.3 are saturated in the

CCD frames, and stars fainter than 14.7 are too close to the faint limit of the APM photometry. However, the range of magnitudes and colors of the bulge giants with spectra is well covered. Our calibration of the APM magnitudes yields the dispersions $\sigma_B = 0.23$, $\sigma_R = 0.09$, and $\sigma_I = 0.12$. Note the large dispersion in the B band.

For the calibration grid, we have used the B-V color as the temperature indicator, all the standards measured (field and cluster stars) have accurate known B-V colors. The other choices are B-I, which gives a longer baseline, or J-K, which is less reddening sensitive. However, most of the standards do not have these colors.

Since our calibration grid is based on $B - V$ colors, we have transformed the $B - R$ colors (the measured colors that are closest in wavelength) via the relationships:

$$B - V = 0.58(B - R) + 0.05$$

derived from Bessell (1986). This relation is not very dependent on $[\text{Fe}/\text{H}]$. These colors are shifted with respect to the Johnson (1964) colors by about 0.05 mags. Also, they are shifted with respect to the photometry of G and K giants presented by McWilliam (1991) by about 0.03 mags, although his data are also in the Johnson filter system.

The $(B - V)$ colors could be systematically off by ≤ 0.10 magnitudes, due to a) uncertainty in the transformations described above, and b) uncertainty in the mean reddening value. A systematic shift of 0.10 mags in the derived $(B - V)$ color would result in a 0.0, 0.1 and 0.2 dex error in the abundances

around $[Fe/H] = -2.0, -1.0$, and 0.0 , respectively. This uneven effect in the abundances is due to the convergence of the isoabundance lines towards the blue in the $Mg + 2Fe, (B - V)$ plane, as seen in figure 10 of chapter 2.

We have chosen B-R rather than R-I because the latter is not a good indicator of temperature below $T_{eff} = 4300^\circ$ for Solar metallicity stars (e.g. McWilliam 1990).

The reddening is nonuniform across the field, as it is in every single bulge window. The question is by how much. The APM photometry provides a mean to estimate this just by number counts. Over a 2×2 degree field, the reddening varies by about 0.20 magnitudes (Irwin 1989). The local corrections for this differential reddening are incorporated in the initial APM photometry, the correction being made in regions of 10×10 arcmin. Even though corrections on smaller scales than that are not made, the systematic reddening has been taken into account, reducing the reddening variations across the field to $\Delta E(B - V) \leq 0.05$. The absolute value adopted for the center of the field is $E(B - V) = 0.17$.

The optical CMDs (figure 1) show a bulge red giant branch well separated from the disk main sequence. This giant branch is wide, unlike that of the giant branch of a typical globular cluster, due to the combined effects of metallicity spread, reddening variations and line-of-sight depth. The horizontal branch of the bulge is clearly seen at $R \sim 15$. In this field, we expect approximately the same number of bulge stars per unit area as that of Terndrup's (1988) field at $l = -8$.

The BRI photometry can also be used to estimate the mean metallicity in this field, by using the slope of the upper RGB (e.g. Ortolani et al. 1991).

Comparing the F588 CMDs with the position of the RGB of the metal rich globular clusters NGC6528, NGC6356, NGC6553, 47Tuc, and Ter1 from Ortolani et al. (1990, 1991, 1992), we estimate $[\text{Fe}/\text{H}] = -0.4 \pm 0.3$ in the mean for F588.

The optical photometry is complemented with extensive near-IR photometry, discussed in more detail in a subsequent paper. We briefly describe here these data. The central 20×20 arcmin of field F588 was imaged with the Nicmos2 array at the 61 Telescope of Steward Observatory, with the JHK near-IR filters. Color-color and color-magnitude diagrams were constructed, to check on the completeness of the selection procedure, and to study further the stellar population in the field. In particular, these data help constrain the reddening, and the presence of field dwarf contamination.

The near-IR CMDs (figure 2) also show a well defined RGB for the bulge. The RGB for this field is much narrower than that of the BW field or the F589 field, but still shows a color range that is consistent with a spread in metal abundances. The red horizontal branch clump is seen at $K \sim 13$, with a depth in K magnitudes of ~ 1.5 mags. There is no obvious blue HB or MS stars present in the IR CMDs. Deeper IR photometry that reaches the turn-off has been obtained. These data show the disk main sequence at magnitudes fainter than the limiting magnitude of figure 2.

Finally, a few bulge giants were selected by magnitudes and colors obtained with the iris photometer at KPNO. These were roughly calibrated with standards from the globulars clusters NGC6642 and NGC6356, which are on the same plates as the fields studied here. The calibration was found to be very crude,

Figure 4.1 APM BRI color-magnitude and color-color diagrams for a 1×1 degree field.

Figure 4.2 JHK color-magnitude and color-color diagrams for a 5×5 arcmin field.

although good enough to discriminate bulge giants. This was done at the beginning of the project in 1989, before we decided to work with the APM magnitudes which are much better.

4.3. The Spectroscopy

The observations and reductions are described in chapter 2, here we give a brief summary. The APM scans produced coordinates good enough for the positioning of fibers with modern multi-object spectrographs (≤ 1 arcsec). Then, the great majority of our spectroscopic sample is based on the three color APM data, the rest of the positions (for the IRIS data) were measured with the Grant machine at KPNO headquarters. The spectroscopic observations were done in the period from 1989 to 1993 at the MMT with the Red Channel spectrograph, at the 90" telescope of Steward Observatory with the MX Multifiber Spectrograph, and at the CTIO 4m telescope with the Argus Multifiber Spectrograph.

With Argus we used the RC spectrograph with the 632-line grating KPGL1 blazed at 4200 Å. This setup gives ~ 2.5 Å resolution, leading to velocities accurate to ≤ 12 km s $^{-1}$, and with enough S/N for reliable abundance estimates. The exposure time was ~ 40 min, about 20 fibers produced good S/N spectra per fiber configuration. The fields were observed above 1.5 airmasses, during bright time. A HeAr comparison lamp was taken immediately after each object exposure. The spectral coverage is from 4700 to 5700 Å. About 200 stars were observed in this run with $S/N \geq 10$ per pixel. With Argus we observed a variety of giants in globular and open clusters that are used as metal abundance and

luminosity standards. Several cluster radial velocity standards were observed in 47Tuc, NGC 1851, NGC 288, and NGC 362 to reduce to the standard velocity system.

With the MX spectrograph we used the 800×800 TI CCD chip and an 1200 line grating in 2nd order blazed at $5200 \text{ \AA}$, obtaining a resolution of $\sim 2 \text{ \AA}$. For a scale of $0.75''/\text{pixel}$ the width of the fibers is equivalent to about 170 km s^{-1} . A HeNeAr comparison lamp was taken immediately after each object exposure. The spectral coverage is from 4550 to $5400 \text{ \AA}$. About 70 stars were observed in the this field with $S/N \geq 5$ per pixel with MX. The exposure times for the program stars ranged from 55 to 70 minutes.

The spectra obtained at the MMT Red Channel in two nights in July 1988 have a spectral coverage from 4600 to $5350 \text{ \AA}$. We used the 800×800 TI CCD chip and an 800-line grating in 2nd order blazed at $5000 \text{ \AA}$, the resulting resolution was $\sim 1.8 \text{ \AA}$. HeNeAr comparison lamps were taken immediately after each object exposure. We have about 40 spectra for this field with $S/N \geq 5$ from the MMT run, 15 of them being field stars (i.e. stars not selected by the photometry). Typical exposure times were between 20 and 30 minutes. The slit size projected on the sky is $1.5 \times 180 \text{ arcsec}$. We have selected typically 2–3 stars aligned on the sky, and rotated the instrument to accommodate them on the slit at the same time. The seeing varies between 1 and 2 arcsec. The exposures were long enough, that the 5 MMT mirrors needed stacking after every 1-2 exposures. This ensured that the stars did not spend most of the time on one side of the slit, giving the wrong radial velocities. This was confirmed by multiple exposures.

Even though the standards required very short exposures, it was possible to center them carefully, so that gross velocity errors were also avoided.

Finally, we obtained 11 spectra ($S/N \approx 10$) with the Steward 90" telescope with Reticon detector during two nights in June 1989. These have a spectral coverage from 4000 to 6000 Å, a dispersion of 2 Å/pix and a resolution of ~ 4 Å. Exposure times were ~ 45 min.

In each of the MMT and 90 " runs we observed between 3 and 5 RV standards from the IAU lists, usually at the beginning , middle and end of the night. We have also taken MX spectra of about 15 stars in the globular cluster M3 with well known radial velocities (from Pryor, Latham and Hazen 1986) in each of the MX nights.

All the standards were observed to widely different S/N, from very high to that of our worst program stars, which allowed a better determination of the true errors involved in the abundance, gravity and RV determinations.

4.4. The Reductions

The MX and Red Channel data reduction was summarized in paper I. Here we briefly describe the Argus data reductions. The Argus reductions were done following the procedures of Suntzeff et al. (1993), we will give only an outline here. The reductions of the Argus data (overscan and bias subtraction, flat-fielding) were done following standard procedures within the IRAF environment, with the routines in the package CCDRED. Then the spectra were extracted in IRAF within the ARGUS package, following the recipes kindly provided by Dr.

N. Suntzeff. The fibers were corrected to give uniform transmission using a very high S/N sky exposure. The one dimensional spectra were wavelength calibrated interactively and rebinned to the same dispersion and wavelength coverage. The sky subtraction was also done interactively, and locally, medianing the nearby 4 fibers to account for local focus changes. The subtraction of the sky scaled by the exposure time sometimes did not completely remove for the sky line at 5577.5 Å. In these cases (which were never greater than 10 % in the sky counts), the sky was scaled properly until the residual 5577.5 Å line disappeared. Particular care was taken at that point because any residual emission line would bias the radial velocity determinations, more for the low S/N spectra. For all the program stars no extinction correction or flux calibration was attempted. However, the sky spectra was checked to see that there were only a few percent continuum variations from fiber to fiber.

4.5. The Velocities

The Argus radial velocities were determined using the cross correlation technique (Tonry and Davis 1979) using the package RVEL within IRAF. The spectra are extracted on a logarithmic scale of 1024 channels, flattened by fitting a 4th order polynomial and masked over the edges with a cosine bell to minimize ringing. Then the frequencies higher than the resolution and much lower than the broadest spectral features were filtered away. The velocity shifts relative to the standard star templates were determined by fitting parabolas to the upper 50 % of the cross correlation peak. For $S/N \sim 10$ the R parameter of Tonry

and Davies (1979) turns out to be ~ 8 respectively. Stars with $S/N \leq 10$ are not considered because the errors in velocities are greater than $\sim 20 \text{ km s}^{-1}$.

As discussed in chapter 2, the errors in the velocities are about 6 km s^{-1} for the MX and MMT data, and 12 km s^{-1} for the Reticon data. For the Argus data, radial velocities good to $\leq 10 \text{ km/s}^{-1}$ are achieved, depending on S/N . Measuring the radial velocities of a typical standard cluster like 47 Tuc yields a velocity dispersion of $\sigma = 14$ and 12 km s^{-1} for the nights of August 1 and 2, respectively. Since the intrinsic velocity dispersion for this cluster is $\sigma_{47Tuc} = 9 \text{ km s}^{-1}$, the residual errors in the velocities are $\sigma_0 = 7$ and 5 km s^{-1} for the first and second night, respectively. All the radial velocities for the ARGUS data were referred to the the mean of the 47Tuc velocities by Mayor et al. (1984), since this cluster was observed with high S/N and the same fiber configuration in both nights, although the spectra were independently correlated with the nightly standards and twilight sky. Difference in velocities for the standards determined in the different nights were always less than 10 km/s .

The heliocentric velocities were then corrected to the Local Standard of Rest assuming a peculiar solar motion of 15.4 km s^{-1} towards $l, b = (51, 23)$ taken from Delhaye (1965). The Galactocentric velocities were obtained by adding $220 \sin(l) \cos(b)$, the correction for the solar orbit around the Galaxy (Gunn, Knapp & Tremaine 1979), where l and b are the Galactic coordinates of the bulge fields.

4.6. The Abundance Determinations

McWilliams & Rich (1993) find that the Rich (1988, hereafter R88) abundance scale is too metal rich by about 0.35 dex . This raises severe doubts

about the whole procedure of determining abundances from the Mg and Fe 5270–Fe5335 indices. This is very unfortunate since much of the extragalactic work is based on these (e.g. extragalactic globular clusters Brodie & Huchra 1991, or elliptical galaxies Burstein et al. 1983, Worthey et al. 1993). In the following we try to redeem the general procedure of getting reliable abundances from the Mg and Fe indices measured in medium resolution spectra ($1\text{--}2\text{ \AA pix}^{-1}$). For that we have measured a variety of indices in a large number of giants in several open and globular clusters, spanning a wide range in metallicities, as well as field giants with well determined parameters.

The main problem with the R88 calibration is that he also relied on field giants as standards, for which the [Mg/Fe] ratios and ages are unknown. Our procedure of using a uniform stellar population such as that of the Galactic globulars avoids the problems of unknown ages, and to a certain extent also the problem of unknown [Mg/Fe] abundances.

We have adopted the Zinn scale, as revised by Armandroff (1989) and Armandroff & Zinn (1991). The only cluster for which a different metallicity is assumed is M4, for which recently Drake et al. (1992) have determined $[\text{Fe}/\text{H}] = -1.05 \pm 0.02$, from high dispersion echelle spectra and model atmospheres of 4 giants.

The clusters and the calibration are discussed in chapter 2. We have used only globular clusters to calibrate the bulge giants. The rationale is that we do not know precisely what the [A/Fe] ratios are for Mg, Ti, O, Ca, etc, in bulge giants. But we assume that whatever the chemical evolution of the clusters, the

bulge giants share the same chemical history. It should be noted that this is an important assumption. It is safer than using local disk giants or open clusters for the calibration, since the chemical evolution of the local disk is most certainly different from that of the bulge. In consequence, all the $[\text{Fe}/\text{H}]$ values obtained here are in the metallicity system of the globular clusters.

To obtain luminosity classifications and metallicity estimates we define in chapter 2 a set of spectrophotometric indices of line intensities following Faber *et al.* (1985) and Friel (1988). Each index is defined as the ratio of the average flux in the central feature passband to that of the continuum passbands located at the sides, and it is expressed in terms of magnitudes. A set of 7, 7 and 5 indices are measured for the MX, Argus, and MMT data, respectively.

We did not measure the indices for any of the 11 stars from the Reticon run. The indices Fe4680, Fe5335, and Fe5400 for the MMT spectra, the index Fe5400 for the MX spectra, and the index Fe4680 for the Argus spectra were not measured because they were out of the wavelength range covered.

The spectroscopic indices for the different telescopes and instrument setups agree with each other, provided small zero point offsets are applied. These shifts are: $\Delta Mg = 0.04$, $\Delta Fe5270 = 0.00$, and $\Delta Fe5335 = 0.02$, in the sense Argus minus MX or MMT. The MX and MMT scales have the same zero point. Note that these zero point offsets are of the order or smaller than the scatter in the index measurements.

In summary, for the MX and MMT data, relative velocities are good to $\sim 7 \text{ km s}^{-1}$ rms, the absolute velocities to $\sim 10 \text{ km s}^{-1}$, and the errors in

the spectral indices to be $\sigma(\text{Mg}) = 0.05$, $\sigma(\text{Fe}4680) = 0.04$, $\sigma(\text{Fe}4590) = 0.04$, $\sigma(\text{Fe}4920) = 0.04$, $\sigma(\text{Fe}5011) = 0.05$, $\sigma(\text{Fe}5270) = 0.04$, and $\sigma(\text{Fe}5335) = 0.03$ for the spectra with $S/N \geq 5$. For the Argus data, relative velocities are good to $\sim 9 \text{ km s}^{-1}$ rms, the absolute velocities to $\sim 12 \text{ km s}^{-1}$, and the errors in the spectral indices to be $\sigma(\text{Mg}) = 0.05$, $\sigma(\text{Fe}4680) = 0.04$, $\sigma(\text{Fe}4590) = 0.04$, $\sigma(\text{Fe}4920) = 0.04$, $\sigma(\text{Fe}5011) = 0.05$, $\sigma(\text{Fe}5270) = 0.04$, and $\sigma(\text{Fe}5335) = 0.03$ for the spectra with $S/N \geq 8$. We stress that even when the instrumental setups and the calibrations were different, the good agreement supports the accuracy of the data.

The errors in the spectroscopic indices are well known, from repeated observations of individual stars. These errors are comparable for all the observing runs, and depend mostly on the signal to noise of the spectrum, but also on abundance itself. For $S/N \geq 8$ the errors are: $\sigma_{MG} = 0.06$, $\sigma_{Fe5270} = 0.04$, $\sigma_{Fe5335} = 0.04$.

In chapter 2 we find that the scatter of the indices of individual stars within a cluster increases for increasing metallicity. This effect is not due to observational errors, since the spectroscopic indices should be better measured for the metal rich stars with stronger features, but it could be due to the onset of molecular absorption, in particular MgH. Stars of the same iron abundance (i.e. stars members of a cluster), show variations in MgH strength, variations that increase for increasing $[\text{Fe}/\text{H}]$. From the different clusters we obtain: $\sigma_{MG} = 0.03, 0.04$, and 0.07 , $\sigma_{Fe5270} = 0.04, 0.05$, and 0.06 , $\sigma_{Fe5335} = 0.04, 0.05$, and 0.07 for $[\text{Fe}/\text{H}] = -2.0, -1.0$ and 0.0 , respectively. These uncertainties, combined with

the photometric uncertainties discussed above, translate into total errors for the individual metallicity derived for a single star of: $\sigma_{[Fe/H]} = 0.10, 0.15$, and 0.25 for $[Fe/H] = -2.0, -1.0, 0.0$, respectively.

The whole abundance scale is uncertain by a zero point error of 0.15 dex (chapter 2). This zero point error will not have a major effect in the dependences of kinematics on metallicity discussed below.

Note that Minniti et al. (1992) neglected the stars with strong Mg indices, on an effort to account for possible dwarfs. However, as we show in Appendix 1, the dwarfs do not pose a significant contribution in this field. Instead, most of the strong Mg stars will be very metal rich giants. Therefore, we will take them into account.

4.7. The Data

In this section we present the data for all the observed giants. Table 1 presents the spectral indices measured for each star. Table 2 presents the photometry, radial velocities, and derived metallicities.

We have divided the sample according to magnitude. The group of stars brighter than $R = 12.3$ is found not to include bulge giants (as shown later in figure 6). The stars with $R \leq 12.3$ are divided according to metallicity. Table 3 gives the mean Galactocentric velocity and velocity dispersion for different metallicity intervals. Column 1 is the abundance range, column 2 is the mean velocity with the standard error of the mean, column 3 is the velocity dispersion with its respective error, and column 4 gives the number of stars considered.

Table 4.1

SPECTROSCOPIC INDICES

Star	H β	Mg	Mg1	Mg2	Mgb	MgH	Fe492	Fe498	Fe50	Fe52	Fe53	Fe54
1	0.77	0.84	0.81	1.02	0.77	0.68	0.67	0.89	0.83	0.83	0.69	0.63
3	0.95	0.82	0.81	0.89	0.83	0.77	0.72	0.92	0.81	0.81	0.84	0.78
5	0.64	0.84	0.85	0.93	0.88	0.65	0.72	0.87	0.81	0.78	0.83	0.80
7	0.69	1.01	0.98	1.08	0.71	0.95	0.69	0.83	0.82	0.73	0.95	0.85
9	0.77	1.20	1.16	1.26	0.89	1.08	0.59	0.95	0.86	0.83	0.89	0.79
10	0.78	0.95	0.89	1.04	0.94	0.72	0.62	1.16	0.85	0.78	0.87	0.81
12	0.51	1.00	1.13	1.20	1.06	0.85	0.47	0.69	0.71	0.95	0.91	0.92
14	0.91	0.95	0.88	1.15	0.87	0.64	0.65	0.73	0.77	0.83	0.83	0.78
16	0.80	0.98	0.84	1.11	0.81	0.80	0.75	0.98	0.94	0.81	0.84	0.78
18	0.32	1.15	1.36	1.37	1.03	1.01	0.62	0.90	0.74	0.95	0.90	0.87
20	0.75	1.18	1.05	1.16	0.82	1.14	0.79	1.04	0.90	0.90	0.91	0.86
22	0.88	1.01	1.25	1.11	1.11	1.24	0.73	0.97	0.84	0.94	0.98	0.82
24	0.61	1.01	1.21	1.25	0.79	1.09	0.91	1.52	1.01	1.01	1.00	0.87
25	0.80	1.11	1.13	1.28	0.85	1.32	0.69	0.77	0.74	0.82	0.99	0.83
27	0.80	0.94	0.94	1.03	0.91	0.88	0.75	0.96	0.85	0.79	0.90	0.83
29	0.85	1.00	0.94	1.08	0.97	0.73	0.73	0.80	0.79	0.89	0.94	0.84
32	0.75	0.86	0.75	0.95	0.92	0.62	0.69	1.02	0.79	0.84	0.81	0.79
34	0.88	0.89	0.88	1.05	0.90	0.72	0.66	0.93	0.88	0.85	0.73	0.82
36	0.52	1.02	0.93	1.06	0.81	0.76	0.76	0.90	0.83	0.87	0.82	0.71
38	0.77	1.12	1.09	1.18	0.93	0.75	0.63	0.84	0.84	0.83	0.75	0.80
40	0.87	0.91	0.89	1.03	0.86	0.71	0.68	0.87	0.83	0.86	0.76	0.76
42	0.81	1.03	1.02	1.07	0.87	1.03	0.75	0.95	0.85	0.89	0.87	0.81
44	0.73	1.05	1.29	1.36	0.81	1.12	0.72	0.73	0.89	0.91	0.89	0.83
46	0.86	1.27	1.27	1.25	0.92	1.17	0.74	0.85	0.74	0.87	1.03	0.84
48	0.74	0.96	0.95	1.14	0.83	0.79	0.68	0.83	0.80	0.89	0.90	0.76
50	0.84	1.13	1.12	1.25	0.90	0.92	0.71	0.87	0.83	0.88	0.81	0.79
52	0.70	0.99	0.95	1.10	0.92	0.73	0.59	0.88	0.82	0.86	0.87	0.81
55	0.75	1.07	1.00	1.04	0.89	0.79	0.76	0.82	0.79	0.78	0.93	0.84
57	0.71	1.09	1.06	1.22	0.94	1.06	0.67	0.83	0.74	1.01	0.95	0.81
59	0.69	0.89	0.90	1.00	0.72	0.71	0.68	0.78	0.80	0.86	0.80	0.84
61	0.87	1.06	1.06	1.18	0.85	1.12	0.70	0.91	0.84	0.83	0.92	0.79
63	0.63	1.10	1.08	1.18	0.70	0.99	0.65	0.89	0.81	0.93	0.83	0.83
65	0.89	1.20	1.24	1.30	0.95	1.10	0.67	0.97	0.87	0.91	0.85	0.79
67	0.67	0.96	0.91	1.11	0.90	0.71	0.66	0.72	0.75	0.88	0.89	0.82
69	0.74	1.09	1.06	1.18	0.90	1.03	0.70	0.83	0.75	0.87	0.87	0.83
71	0.83	1.01	0.95	1.13	0.78	0.72	0.62	0.83	0.76	0.78	0.86	0.78
25	0.97	1.08	1.31	1.13	1.35	1.26	0.15	1.28	1.10	0.94	0.86	0.63
26	0.96	0.79	0.75	0.95	0.72	0.79	0.65	0.86	0.77	0.74	0.86	0.81
74	0.85	1.13	1.11	1.25	0.90	0.95	0.66	0.87	0.82	0.89	0.83	0.82
76	0.32	1.16	1.15	1.41	0.88	0.93	0.67	0.97	0.87	0.86	0.96	0.81
78	0.94	0.74	0.62	0.65	0.76	0.48	0.77	0.81	0.78	0.84	0.93	0.84
80	0.84	1.17	1.11	1.27	0.92	0.80	0.71	1.04	0.87	0.95	0.78	0.84
82	0.78	0.96	0.96	1.05	0.85	0.72	0.69	0.92	0.83	0.86	0.68	0.61
84	0.69	1.05	1.06	1.20	1.21	0.77	0.59	0.81	0.69	0.90	0.87	0.91
86	0.00	1.74	1.94	2.12	1.75	2.12	0.00	0.06	0.00	0.69	0.95	0.79
88	0.66	1.12	0.99	1.17	0.68	1.01	0.71	1.16	0.96	0.91	0.90	0.80
90	0.88	1.23	1.19	1.26	1.00	0.95	0.59	1.11	0.93	0.87	0.81	0.84

Star	H β	Mg	Mg1	Mg2	Mgb	MgH	Fe492	Fe498	Fe50	Fe52	Fe53	Fe54
92	0.77	1.04	0.91	1.10	0.87	0.85	0.64	1.09	0.87	0.98	0.94	0.78
94	0.95	1.06	1.04	1.11	0.90	0.99	0.71	0.82	0.77	0.89	0.90	0.80
96	0.82	1.15	1.14	1.27	0.91	0.96	0.67	0.81	0.74	0.88	0.97	0.85
97	0.76	0.74	0.67	0.75	0.85	0.47	0.78	0.91	0.82	0.75	0.85	0.76
99	2.93	0.85	0.91	0.92	1.08	0.62	0.08	0.00	0.82	0.69	1.09	0.88
101	1.59	0.35	0.10	0.57	0.19	0.71	1.24	0.00	0.80	0.66	1.83	1.41
103	0.78	1.12	1.15	1.06	0.85	1.04	0.67	0.70	0.86	0.83	0.94	0.96
105	0.63	0.89	0.74	0.98	0.69	0.82	0.74	1.32	0.88	0.79	0.67	0.86
107	0.81	0.82	0.71	0.84	0.78	0.63	0.73	0.83	0.77	0.74	0.88	0.85
109	0.45	1.56	1.35	1.45	1.76	0.40	0.97	0.25	0.91	0.83	1.02	0.61
111	3.49	1.12	1.25	2.51	0.10	2.08	0.00	0.00	1.13	0.63	0.83	0.75
113	1.30	1.22	1.24	1.44	1.01	1.08	0.79	0.99	0.84	0.88	0.87	0.87
115	0.70	1.03	1.05	1.12	0.78	0.72	0.81	0.93	0.90	0.92	0.90	0.70
117	0.87	0.94	0.90	1.05	0.85	0.68	0.78	0.88	0.82	0.83	0.77	0.76
119	0.61	2.02	1.96	1.80	2.22	1.12	0.00	0.00	0.02	1.06	1.19	0.88
1	0.88	0.98	0.97	1.14	0.83	0.73	0.69	0.94	0.86	0.89	0.78	0.81
3	0.59	0.97	0.96	1.26	0.56	1.08	0.52	0.99	1.10	1.14	0.76	1.01
5	0.69	1.07	0.99	1.23	0.93	0.87	0.69	0.91	0.84	0.98	0.89	0.88
7	0.60	1.16	1.11	1.25	0.97	0.91	0.65	1.03	0.83	0.86	0.76	0.78
9	0.85	1.04	1.03	1.18	0.89	0.80	0.69	0.94	0.87	0.88	0.78	0.81
11	0.52	1.18	1.95	2.23	0.78	2.07	0.45	1.23	1.17	0.87	0.95	0.80
13	0.70	1.04	0.94	1.12	0.93	0.74	0.67	0.84	0.78	0.93	0.95	0.83
15	0.73	1.06	1.05	1.17	0.83	0.84	0.68	0.95	0.87	0.90	0.92	0.84
17	0.79	1.07	0.99	1.18	0.84	0.84	0.72	0.90	0.81	0.83	0.92	0.85
19	0.76	0.97	0.91	1.14	0.93	0.72	0.63	0.93	0.83	0.90	0.88	0.80
21	0.71	0.99	0.90	1.11	0.97	0.70	0.68	0.91	0.83	0.89	0.82	0.80
23	0.72	1.12	1.06	1.29	0.95	0.89	0.62	0.90	0.76	0.85	0.85	0.81
25	0.51	1.12	1.28	1.43	0.89	1.07	0.79	0.88	0.91	0.92	0.86	0.83
27	0.92	0.94	0.91	1.08	0.83	0.86	0.71	0.91	0.86	0.83	0.85	0.79
29	0.93	1.20	1.11	1.33	0.90	0.94	0.73	1.05	0.81	0.97	0.93	0.85
31	0.75	1.16	1.11	1.25	0.80	0.91	0.66	0.87	0.83	0.80	0.80	0.78
33	0.66	1.08	1.01	1.22	0.86	0.84	0.73	0.94	0.83	0.83	0.84	0.83
35	0.75	1.30	1.30	1.44	0.92	1.15	0.68	0.99	0.91	0.97	0.89	0.78
37	0.83	0.92	0.82	1.03	0.76	0.60	0.72	0.84	0.80	0.77	0.85	0.79
39	0.78	1.18	1.16	1.27	0.96	1.09	0.46	1.06	0.89	0.86	0.94	0.76
40	1.00	1.05	1.06	1.16	0.89	1.18	0.67	0.94	0.83	0.82	0.82	0.77
42	1.10	1.01	1.01	1.16	0.85	0.77	0.60	1.06	0.85	0.85	0.78	0.82
44	0.72	1.15	1.15	1.30	0.89	0.90	0.80	0.99	0.92	0.96	0.84	0.67
46	0.86	1.10	1.10	1.23	0.91	0.87	0.78	0.99	0.90	0.86	0.82	0.82
48	0.81	1.04	0.95	1.15	0.83	0.75	0.70	0.92	0.82	0.82	0.88	0.81
50	0.72	1.05	1.21	1.53	0.86	1.11	0.75	0.66	0.83	0.84	0.95	0.63
52	0.82	0.92	0.88	1.14	0.88	0.73	0.81	0.94	0.84	0.81	0.81	0.74
54	0.57	1.15	1.48	1.74	0.91	1.80	0.74	0.76	0.94	1.01	0.89	0.80
56	0.94	1.11	1.13	1.23	0.87	0.96	0.72	0.88	0.87	0.91	0.69	0.87
58	0.75	1.07	1.08	1.25	0.86	0.84	0.72	0.94	0.88	0.86	0.88	0.81
61	0.73	1.14	1.10	1.29	1.04	0.77	0.60	0.80	0.78	0.91	0.91	0.81
63	0.51	1.69	1.78	1.87	0.85	1.95	0.00	4.81	2.24	0.88	0.99	0.70
64	0.71	1.05	1.39	1.54	0.99	1.42	0.67	0.92	0.91	0.94	0.94	0.74
66	0.77	0.84	1.53	3.33	0.83	1.05	0.54	0.01	0.13	0.76	0.85	0.79
68	0.69	1.08	1.28	1.54	1.08	1.13	0.95	1.11	1.00	0.99	0.90	0.86
70	0.79	0.88	0.85	1.03	0.84	0.63	0.72	0.92	0.87	0.86	0.73	0.75

Star	H β	Mg	Mg1	Mg2	Mgb	MgH	Fe492	Fe498	Fe50	Fe52	Fe53	Fe54
72	0.82	1.24	1.16	1.36	1.04	0.97	0.61	0.98	0.76	0.95	0.88	0.73
74	0.90	1.17	1.09	1.35	1.04	0.93	0.87	0.79	0.82	0.97	0.99	0.88
76	0.77	1.15	1.14	1.28	0.88	0.99	0.65	0.94	0.86	0.92	0.85	0.81
78	0.61	1.02	1.77	1.82	1.16	1.54	0.09	0.78	0.81	0.90	0.98	0.87
80	0.75	1.09	1.06	1.26	1.04	0.81	0.59	0.85	0.72	0.90	0.85	0.85
82	0.71	1.19	1.11	1.35	0.82	0.97	0.63	0.93	0.83	0.82	0.85	0.84
84	0.92	1.12	1.15	1.25	0.84	0.90	0.61	0.92	0.88	0.83	0.78	0.83
86	0.87	0.96	0.95	1.09	0.85	0.74	0.64	0.91	0.84	0.83	0.78	0.81
88	0.78	0.81	0.72	1.01	0.87	0.60	0.70	0.89	0.82	0.83	0.80	0.75
90	0.83	1.00	0.98	1.12	0.86	0.77	0.65	0.91	0.87	0.85	0.84	0.86
92	0.21	1.03	1.36	1.43	0.87	1.35	0.83	1.29	1.07	0.95	0.85	0.80
94	0.82	1.18	1.17	1.33	0.80	1.09	0.63	1.10	0.92	0.87	0.82	0.77
96	0.95	1.25	1.31	1.34	1.16	1.28	0.31	1.23	1.04	0.93	0.98	0.76
97	0.68	1.40	1.38	1.63	1.07	1.18	0.34	0.99	0.84	0.95	0.93	0.77
99	0.85	0.87	0.85	1.04	0.80	0.60	0.68	0.94	0.87	0.79	0.72	0.76
101	0.72	0.96	0.91	1.08	0.94	0.68	0.68	0.86	0.76	0.86	0.84	0.81
103	0.87	0.92	0.95	1.01	0.96	0.72	0.67	0.92	0.84	0.79	0.78	0.82
105	0.80	1.15	1.18	1.26	0.92	1.19	0.63	0.95	0.82	0.84	0.96	0.84
107	0.92	0.00	0.00	0.00	0.15	0.00	0.79	0.54	0.66	1.34	0.89	0.88
109	0.70	1.23	1.26	1.38	0.92	1.13	0.53	0.95	0.88	0.93	0.92	0.72
111	0.86	1.07	1.08	1.18	0.82	1.10	0.54	0.98	0.84	0.86	0.81	0.78
113	0.76	1.10	1.03	1.24	1.00	0.90	0.66	1.11	0.82	0.88	0.90	0.80
115	0.74	1.09	1.08	1.24	0.86	0.84	0.71	0.89	0.84	0.89	0.86	0.84
117	0.84	1.15	1.08	1.27	0.85	0.94	0.67	0.89	0.79	0.88	0.98	0.80
119	0.63	1.07	1.12	1.33	0.93	1.02	0.50	0.89	0.81	0.97	0.85	0.84
13	1.14	-92.10	0.83	0.71	0.00	0.00	0.82	0.00	0.65	0.79	0.85	0.00
13	1.18	18.00	0.84	0.94	0.00	0.00	0.89	0.00	0.69	0.83	0.83	0.00
13	1.07	94.60	0.94	0.80	0.00	0.00	0.88	0.00	0.69	0.76	0.82	0.00
13	0.92	-33.90	0.83	0.84	0.00	0.00	0.89	0.00	0.76	0.80	0.89	0.00
13	0.84	-186.20	0.76	0.79	0.00	0.00	0.94	0.00	0.75	0.80	0.74	0.00
13	0.99	156.50	0.82	0.78	0.00	0.00	0.88	0.00	0.71	0.81	0.88	0.00
13	1.04	35.00	0.79	0.81	0.00	0.00	0.90	0.00	0.77	0.86	0.82	0.00
13	0.96	78.50	0.81	0.83	0.00	0.00	0.84	0.00	0.73	0.81	0.93	0.00
13	1.13	-24.30	0.89	0.76	0.00	0.00	0.77	0.00	0.55	0.86	0.81	0.00
13	1.18	-33.20	0.91	0.87	0.00	0.00	0.78	0.00	0.67	0.83	0.93	0.00
13	1.05	30.00	0.95	0.90	0.00	0.00	0.90	0.00	0.71	0.83	0.88	0.00
13	0.98	11.80	0.85	0.98	0.00	0.00	0.86	0.00	0.68	0.82	0.89	0.00
13	1.12	38.10	0.83	0.91	0.00	0.00	0.90	0.00	0.78	0.81	0.88	0.00
13	0.92	-88.80	0.82	0.86	0.00	0.00	0.93	0.00	0.82	0.81	0.83	0.00
13	3.80	0.00	0.87	0.80	0.90	0.00	1.06	0.00	0.85	0.68	0.87	0.00
61	1.06	-26.70	0.94	0.86	0.00	0.00	0.87	0.00	0.72	0.83	0.86	0.00
61	0.84	162.10	0.82	0.00	0.00	0.00	0.91	0.00	0.61	0.76	0.79	0.00
61	0.95	88.60	0.86	0.84	0.00	0.00	0.82	0.00	0.63	0.83	0.84	0.00
61	1.00	60.40	0.92	0.84	0.00	0.00	0.90	0.00	0.69	0.84	0.86	0.00
61	0.84	-68.50	0.77	0.93	0.00	0.00	0.76	0.00	0.00	0.72	0.84	0.00
61	1.09	34.10	0.91	0.93	0.00	0.00	0.84	0.00	0.65	0.87	0.85	0.00
61	0.90	-100.00	0.81	0.90	0.00	0.00	0.00	0.00	0.65	0.86	0.80	0.00
61	0.92	14.00	0.89	0.79	0.00	0.00	0.86	0.00	0.73	0.85	0.83	0.00
61	1.01	7.90	0.92	0.80	0.00	0.00	0.85	0.00	0.65	0.86	0.86	0.00
61	0.98	-81.10	0.90	0.74	0.00	0.00	0.80	0.00	0.70	0.81	0.82	0.00
61	0.78	-57.60	0.90	0.60	0.00	0.00	0.75	0.00	0.63	0.78	0.76	0.00

Star	H β	Mg	Mg1	Mg2	Mgb	MgH	Fe492	Fe498	Fe50	Fe52	Fe53	Fe54
61	0.94	-42.10	0.80	0.69	0.00	0.00	0.81	0.00	0.75	0.87	0.85	0.00
61	4.00	0.00	0.84	0.94	0.87	0.00	0.98	0.00	0.88	0.72	0.84	0.00
61	1.10	45.80	0.96	0.75	0.00	0.00	0.86	0.00	0.68	0.79	0.94	0.00
61	0.99	-78.80	0.94	0.88	0.00	0.00	0.84	0.00	0.60	0.76	0.81	0.00
61	1.14	10.20	0.80	0.68	0.00	0.00	0.00	0.00	0.00	0.78	0.85	0.00
61	0.94	-81.20	0.88	0.66	0.00	0.00	0.85	0.00	0.72	0.81	0.81	0.00
61	0.97	-57.20	0.93	0.82	0.00	0.00	0.85	0.00	0.69	0.83	0.87	0.00
61	1.00	-35.90	0.95	0.78	0.00	0.00	0.92	0.00	0.80	0.78	0.84	0.00
61	1.09	-40.90	0.86	0.84	0.00	0.00	0.82	0.00	0.63	0.83	0.84	0.00
9	1.02	46.80	0.91	0.87	0.00	0.00	0.82	0.00	0.72	0.81	0.88	0.00
9	1.01	-134.90	0.76	0.79	0.00	0.00	0.75	0.00	0.80	0.84	0.83	0.00
9	0.95	-34.30	0.82	0.87	0.00	0.00	0.87	0.00	0.76	0.81	0.86	0.00
9	0.96	76.80	0.81	0.81	0.00	0.00	0.86	0.00	0.74	0.79	0.87	0.00
9	0.89	10.30	0.82	0.84	0.00	0.00	0.83	0.00	0.73	0.80	0.83	0.00
9	1.12	-113.10	0.89	0.86	0.00	0.00	0.86	0.00	0.68	0.88	0.88	0.00
9	1.02	-94.70	0.84	0.87	0.00	0.00	0.99	0.00	0.74	0.90	0.86	0.00
9	0.86	153.80	0.81	0.83	0.00	0.00	0.81	0.00	0.75	0.86	0.86	0.00
9	0.85	-21.40	0.78	0.78	0.00	0.00	0.87	0.00	0.77	0.78	0.82	0.00
9	1.04	-150.50	0.84	0.82	0.00	0.00	0.84	0.00	0.74	0.75	0.80	0.00
9	1.10	11.10	0.88	0.92	0.00	0.00	0.90	0.00	0.72	0.82	0.85	0.00
9	0.94	-29.50	0.75	0.83	0.00	0.00	0.85	0.00	0.83	0.85	0.87	0.00
9	0.90	112.30	0.81	0.89	0.00	0.00	0.84	0.00	0.75	0.81	0.88	0.00
9	1.04	1.00	0.90	0.92	0.00	0.00	0.89	0.00	0.66	0.84	0.91	0.00
9	0.69	-335.70	0.77	0.83	0.00	0.00	0.81	0.00	0.75	0.84	0.83	0.00
9	1.02	-21.10	0.85	0.89	0.00	0.00	0.84	0.00	0.68	0.84	0.86	0.00
9	0.83	139.70	0.80	0.86	0.00	0.00	0.86	0.00	0.77	0.79	0.84	0.00
9	0.85	31.10	0.77	0.94	0.00	0.00	0.86	0.00	0.72	0.79	0.74	0.00
9	0.68	-151.30	0.77	0.70	0.00	0.00	0.91	0.00	0.65	0.79	0.74	0.00
9	0.92	57.70	0.87	0.90	0.00	0.00	0.90	0.00	0.77	0.84	0.88	0.00
9	0.85	-78.70	0.81	0.79	0.00	0.00	0.78	0.00	0.64	0.79	0.84	0.00
9	0.81	-73.00	0.83	0.77	0.00	0.00	0.78	0.00	0.72	0.80	0.81	0.00
9	1.09	-68.60	0.87	0.83	0.00	0.00	0.79	0.00	0.61	0.87	0.90	0.00
20	0.97	-26.00	0.00	0.00	0.00	0.00	0.80	0.00	0.74	0.00	0.82	0.00
20	1.06	-21.90	0.00	0.00	0.00	0.00	0.94	0.00	0.53	0.88	0.85	0.00
23	1.06	-81.90	0.00	0.00	0.00	0.00	0.89	0.00	0.48	0.91	0.82	0.00
23	0.99	64.50	0.00	0.00	0.00	0.00	0.90	0.00	0.71	0.00	0.89	0.00
25	0.89	92.80	0.00	0.00	0.00	0.00	0.00	0.00	0.75	0.00	0.84	0.00
25	0.89	-67.30	0.00	0.00	0.00	0.00	0.78	0.00	0.70	0.80	0.83	0.00
27	1.06	9.70	0.00	0.00	0.00	0.00	0.90	0.00	0.72	0.81	0.86	0.00
27	1.04	-54.70	0.00	0.00	0.00	0.00	0.91	0.00	0.59	0.85	0.83	0.00
29	0.88	-201.10	0.00	0.00	0.00	0.00	0.89	0.00	0.68	0.78	0.77	0.00
29	1.01	83.70	0.00	0.00	0.00	0.00	0.88	0.00	0.62	0.81	0.85	0.00
41	0.85	0.80	0.00	0.00	0.00	0.00	0.98	0.00	0.68	0.81	0.83	0.00
41	0.92	35.90	0.00	0.00	0.00	0.00	0.97	0.00	0.69	0.80	0.84	0.00
43	1.06	59.70	0.00	0.00	0.00	0.00	0.95	0.00	0.60	0.86	0.88	0.00
43	0.88	-23.50	0.00	0.00	0.00	0.00	0.97	0.00	0.71	0.83	0.84	0.00
43	0.77	-24.90	0.00	0.00	0.00	0.00	0.93	0.00	0.68	0.79	0.77	0.00
45	0.89	-113.30	0.00	0.00	0.00	0.00	0.90	0.00	0.70	0.80	0.79	0.00
45	0.90	-20.60	0.00	0.00	0.00	0.00	0.93	0.00	0.79	0.80	0.82	0.00
45	1.10	-82.30	0.00	0.00	0.00	0.00	0.98	0.00	0.69	0.83	0.87	0.00
47	0.99	87.40	0.00	0.00	0.00	0.00	0.95	0.00	0.68	0.81	0.84	0.00

Table 4.2 : Photometry, Velocities and Abundances

Star	R	R-I	B-R	Vr	co	[Fe/H]	ST
1	16.10	0.91	1.11	41.8	ARGUS	-1.90	K
2	16.89	1.24	1.87	49.4	ARGUS	-0.65	K
3	15.51	0.85	1.18	-20.3	ARGUS	-1.45	K
4	16.57	0.96	1.64	88.9	ARGUS	0.05	K
5	16.55	0.97	1.30	-166.2	ARGUS	-1.55	K
6	16.53	0.95	1.48	85.1	ARGUS	-0.35	K
7	16.82	1.08	1.82	0.0	ARGUS	-1.05	K
8	16.36	0.85	1.44	150.1	ARGUS	-1.15	K
9	15.82	1.25	1.83	-6.9	ARGUS	-0.25	M
10	16.84	0.90	1.27	10.6	ARGUS	-0.85	K
11	16.81	1.00	1.82	56.1	ARGUS	-1.05	K
12	16.40	0.91	1.23	133.0	ARGUS	0.75	K
13	16.57	1.02	1.11	123.0	ARGUS	-0.85	K
14	16.77	0.99	1.32	24.4	ARGUS	-0.85	K
15	15.93	0.91	1.51	113.2	ARGUS	-0.95	K
16	16.59	0.94	1.41	-5.3	ARGUS	-0.85	K
17	16.40	0.90	1.39	61.4	ARGUS	-0.05	K
18	16.89	1.23	1.68	39.9	ARGUS	0.25	K
19	16.79	1.10	1.84	19.5	ARGUS	0.35	K
20	16.41	1.06	1.67	-6.4	ARGUS	0.25	K
21	16.64	0.86	1.45	29.1	ARGUS	-0.55	K
22	16.76	1.02	1.80	81.7	ARGUS	-0.25	K
23	15.78	0.95	1.87	-21.8	ARGUS	-0.55	K
24	16.76	0.93	1.70	-72.5	ARGUS	0.25	K
25	0.00	0.00	0.00	17.5	ARGUS	...	M
25	16.64	1.04	1.88	-13.8	ARGUS	-0.35	K
26	16.89	1.24	1.87	82.2	ARGUS	-0.55	K
27	16.64	0.97	1.35	-21.1	ARGUS	-0.75	K
28	16.45	0.89	1.59	-78.3	ARGUS	-0.55	K
29	16.73	0.90	1.41	23.9	ARGUS	0.05	K
31	16.80	1.07	1.29	0.0	ARGUS	-1.90	K
32	15.73	0.88	1.41	10.1	ARGUS	-1.35	K
33	15.84	1.19	1.94	-10.1	ARGUS	-0.15	K
34	16.61	0.89	1.14	-45.4	ARGUS	-1.45	K
35	16.31	0.93	1.47	-16.9	ARGUS	-0.95	K
36	16.87	1.03	1.30	43.2	ARGUS	-0.35	K
37	15.99	1.04	1.81	44.7	ARGUS	-0.25	K
38	16.61	1.05	1.76	172.1	ARGUS	-0.95	K
39	16.49	0.89	1.27	-15.4	ARGUS	0.45	K
40	15.66	1.05	1.61	68.8	ARGUS	-1.45	K
41	16.70	0.86	1.62	28.0	ARGUS	0.35	K
42	16.43	0.97	1.40	-22.3	ARGUS	-0.15	K
43	16.63	0.87	1.27	111.1	ARGUS	0.65	K
44	16.62	1.05	1.44	60.7	ARGUS	0.05	K
45	16.74	1.00	1.34	134.3	ARGUS	0.05	K
46	16.76	1.02	1.80	78.8	ARGUS	0.65	K
47	15.56	1.06	1.85	-107.7	ARGUS	-0.95	K
48	15.63	0.90	1.31	38.5	ARGUS	-0.15	K
49	16.07	0.99	1.61	80.2	ARGUS	0.05	K
50	15.52	1.04	1.83	53.2	ARGUS	-0.65	K

Star	R	R-I	B-R	Vr	co	[Fe/H]	ST
51	16.65	1.06	1.34	27.0	ARGUS	0.45	K
52	16.65	0.89	1.31	232.0	ARGUS	-0.25	K
53	16.61	1.07	1.64	-2.7	ARGUS	-0.55	K
55	16.75	0.89	1.55	0.0	ARGUS	-0.45	K
56	15.76	1.00	1.64	322.4	ARGUS	-1.25	K
57	16.86	0.98	1.65	21.7	ARGUS	0.45	K
58	15.98	0.96	1.16	-30.1	ARGUS	-1.55	K
59	16.74	0.89	1.25	134.9	ARGUS	-1.05	K
60	16.90	1.12	1.33	49.1	ARGUS	-0.45	K
61	16.38	0.95	1.15	-12.4	ARGUS	0.75	K
62	15.59	1.08	1.83	146.6	ARGUS	-0.35	K
63	16.09	1.02	1.84	53.9	ARGUS	-0.45	K
64	16.13	1.17	1.92	-17.4	ARGUS	-0.15	K
65	15.86	1.27	1.56	-43.9	ARGUS	0.35	K
66	16.50	1.09	1.46	19.4	ARGUS	0.65	K
67	16.58	0.96	1.79	128.0	ARGUS	-0.85	K
68	16.23	1.28	1.57	23.3	ARGUS	-0.45	K
69	16.08	1.00	1.69	-76.6	ARGUS	-0.45	K
70	16.32	1.03	1.80	-12.6	ARGUS	-0.65	K
71	15.85	0.99	1.82	92.7	ARGUS	-1.15	K
72	16.64	0.93	1.76	40.0	ARGUS	0.45	K
25	0.00	0.00	0.00	26.1	ARGUS	...	M
26	0.00	0.00	0.00	86.8	ARGUS	1.15	K
73	16.70	0.98	1.63	0.0	ARGUS	-1.90	K
74	15.52	1.04	1.83	58.3	ARGUS	-0.55	K
75	15.99	1.04	1.34	-144.1	ARGUS	-1.55	K
76	15.72	0.94	1.53	32.4	ARGUS	0.45	K
77	16.38	1.06	1.87	-33.1	ARGUS	-1.15	K
78	16.73	1.11	1.70	0.0	ARGUS	-1.55	K
79	16.97	1.04	1.53	0.0	ARGUS	-0.45	K
80	16.03	1.14	1.43	-85.8	ARGUS	0.35	K
81	16.73	0.99	1.54	-99.7	ARGUS	-1.70	K
82	16.62	0.87	1.25	140.3	ARGUS	-1.35	K
83	16.84	0.99	1.34	0.0	ARGUS	-1.90	K
84	16.74	1.05	1.37	126.5	ARGUS	0.15	K
85	16.06	1.16	1.87	109.1	ARGUS	-0.15	K
86	16.37	1.43	1.96	98.8	ARGUS	0.95	K
87	16.72	0.91	1.56	-63.7	ARGUS	-0.65	K
88	16.68	0.90	1.84	-98.5	ARGUS	-0.25	K
89	15.82	1.00	1.11	76.3	ARGUS	-0.35	K
90	16.55	0.99	1.76	-78.2	ARGUS	-0.25	K
91	16.58	0.96	1.79	148.9	ARGUS	-0.75	K
92	16.20	0.96	1.55	114.0	ARGUS	0.35	K
93	16.06	1.26	1.97	18.1	ARGUS	-0.15	K
94	16.57	0.97	1.80	75.6	ARGUS	-0.45	K
95	15.84	0.88	1.26	-24.3	ARGUS	0.15	K
96	16.42	0.87	1.61	90.3	ARGUS	0.35	K
25	0.00	0.00	0.00	12.6	ARGUS	...	K
97	15.97	0.99	1.89	0.0	ARGUS	-1.90	K
98	16.64	1.06	1.62	34.9	ARGUS	-1.35	K
99	16.67	0.98	1.81	-168.0	ARGUS	-1.15	K

Star	R	R-I	B-R	Vr	co	[Fe/H]	ST
100	16.38	0.95	1.35	5.9	ARGUS	-0.15	K
101	16.65	0.91	1.48	0.0	ARGUS	-0.05	K
102	16.03	1.12	1.75	0.0	ARGUS	-1.90	K
103	16.17	1.02	1.75	0.0	ARGUS	-0.25	K
104	15.53	1.55	1.71	42.2	ARGUS	-0.45	K
105	16.68	1.06	1.20	0.0	ARGUS	-1.90	K
106	16.85	1.33	1.80	12.4	ARGUS	-1.25	K
107	17.00	1.13	1.24	0.0	ARGUS	-1.55	K
108	16.58	1.10	2.03	0.0	ARGUS	-0.75	K
109	16.70	1.01	1.47	0.0	ARGUS	1.15	K
110	15.72	1.31	2.06	153.0	ARGUS	-0.65	K
111	15.70	0.85	1.36	153.7	ARGUS	-1.05	K
112	16.69	0.95	1.86	100.6	ARGUS	0.05	K
113	16.14	1.08	1.78	58.4	ARGUS	-0.05	K
114	16.63	0.94	1.23	-11.8	ARGUS	0.35	K
115	16.40	0.99	1.50	41.0	ARGUS	-0.05	K
116	16.34	1.11	1.73	-14.9	ARGUS	-0.55	K
117	16.20	0.92	1.22	-75.3	ARGUS	-1.05	K
118	16.38	0.90	1.13	-10.1	ARGUS	0.65	K
119	16.72	0.94	1.30	-5.5	ARGUS	1.15	K
120	16.65	0.89	1.77	177.2	ARGUS	-0.55	K
1	16.34	0.91	1.57	41.2	ARGUS	-0.95	K
2	16.12	1.15	1.25	18.3	ARGUS	-0.25	K
3	16.98	1.10	1.84	-18.4	ARGUS	-0.45	K
4	16.63	1.13	1.69	81.3	ARGUS	0.45	K
5	16.89	0.99	1.37	3.4	ARGUS	0.65	K
6	16.84	1.01	1.47	3.5	ARGUS	0.65	K
7	16.78	0.96	1.52	-110.2	ARGUS	-0.35	K
8	16.64	1.02	1.57	105.2	ARGUS	-0.75	K
9	15.95	0.94	1.64	46.3	ARGUS	-0.85	K
10	16.65	0.89	1.31	175.8	ARGUS	-0.15	K
11	16.77	1.17	1.64	-134.2	ARGUS	0.35	K
12	16.82	1.06	1.43	120.6	ARGUS	0.25	K
13	16.76	0.93	1.38	91.7	ARGUS	0.55	K
14	15.84	0.88	1.26	-38.7	ARGUS	0.35	K
15	16.76	0.93	1.70	-76.7	ARGUS	0.25	K
16	15.76	1.72	2.07	141.3	ARGUS	-0.55	M
17	16.64	1.03	1.19	-18.6	ARGUS	0.65	K
18	16.70	0.89	1.56	-129.4	ARGUS	-1.90	K
19	16.80	0.86	1.11	8.3	ARGUS	0.45	K
20	16.68	1.03	1.67	-91.0	ARGUS	0.15	K
21	16.33	0.92	1.34	-10.3	ARGUS	-0.45	K
22	16.56	0.93	1.17	69.6	ARGUS	0.85	K
23	16.21	1.05	1.52	-98.9	ARGUS	-0.15	K
24	16.86	1.01	1.53	-101.0	ARGUS	-0.75	K
25	16.90	1.04	1.72	154.2	ARGUS	-0.15	K
26	15.65	1.88	2.13	-1.2	ARGUS	-0.55	M
27	16.46	0.87	1.19	-35.1	ARGUS	-0.55	K
28	16.25	0.91	1.12	-133.4	ARGUS	-1.55	K
29	16.88	0.97	1.79	100.8	ARGUS	0.35	K
30	16.84	1.01	1.47	10.6	ARGUS	1.15	K

Star	R	R-I	B-R	Vr	co	[Fe/H]	ST
31	15.87	1.11	1.47	-127.7	ARGUS	-0.35	K
32	16.41	0.97	1.69	-38.7	ARGUS	-0.35	K
33	16.77	1.06	1.17	-125.7	ARGUS	0.25	K
34	15.85	1.40	1.75	-60.5	ARGUS	-0.15	M
35	15.89	1.06	1.98	32.1	ARGUS	0.25	K
36	16.33	1.16	1.87	67.9	ARGUS	0.05	K
37	16.64	0.89	1.14	85.7	ARGUS	-0.95	K
38	15.84	0.88	1.26	-39.6	ARGUS	-0.25	K
39	16.02	1.33	2.15	-9.7	ARGUS	-0.45	M
40	15.85	0.88	1.56	-42.7	ARGUS	-0.75	K
41	16.45	0.89	1.14	108.4	ARGUS	-0.05	K
42	16.44	0.91	1.21	41.1	ARGUS	-0.55	K
43	16.27	0.92	1.66	-115.2	ARGUS	-0.45	K
44	16.52	0.98	1.27	27.3	ARGUS	1.05	K
45	16.54	0.88	1.16	-2.6	ARGUS	0.45	K
46	16.86	0.92	1.45	-53.9	ARGUS	-0.25	K
47	16.67	0.89	1.12	110.0	ARGUS	0.75	K
48	15.61	0.90	1.24	-22.2	ARGUS	0.05	K
49	16.73	0.97	1.56	83.7	ARGUS	0.35	K
50	16.96	1.16	1.82	25.5	ARGUS	-0.55	K
51	16.37	0.91	1.42	-48.6	ARGUS	-1.55	K
52	16.10	0.86	1.62	-74.5	ARGUS	-1.35	K
53	16.22	1.47	1.90	61.9	ARGUS	-0.15	M
54	16.65	1.11	1.58	65.5	ARGUS	0.65	K
55	16.40	0.97	1.31	39.6	ARGUS	-1.05	K
56	16.92	1.01	1.64	-62.6	ARGUS	-0.75	K
57	16.82	1.10	1.43	36.1	ARGUS	-0.15	K
58	16.36	0.98	1.27	-83.3	ARGUS	0.35	K
60	15.52	1.04	1.83	30.7	ARGUS	-0.85	K
61	16.03	1.12	1.79	1.5	ARGUS	-0.05	K
62	16.65	0.89	1.77	82.0	ARGUS	0.05	K
63	16.02	1.33	2.15	-22.4	ARGUS	1.15	M
64	16.62	0.87	1.50	24.5	ARGUS	0.35	K
65	16.75	0.96	1.61	26.0	ARGUS	0.15	K
66	15.87	0.87	1.19	3.0	ARGUS	-1.55	K
67	16.95	1.04	1.18	90.3	ARGUS	0.75	K
68	16.56	0.96	1.63	-12.0	ARGUS	0.25	K
69	16.62	0.93	1.31	-79.9	ARGUS	-0.85	K
70	16.76	0.91	1.37	141.1	ARGUS	-1.55	K
71	15.95	1.16	1.28	-170.5	ARGUS	-1.90	K
72	16.81	1.08	1.99	-8.0	ARGUS	-0.05	K
73	16.21	1.38	1.55	112.4	ARGUS	1.15	M
74	16.82	1.03	2.10	10.7	ARGUS	0.05	K
75	16.55	1.58	1.67	15.6	ARGUS	0.25	K
76	16.02	0.98	1.67	51.9	ARGUS	-0.05	K
77	16.04	1.06	1.59	90.5	ARGUS	-0.95	K
78	16.65	1.11	1.58	73.8	ARGUS	0.45	K
79	16.69	0.89	1.13	-67.9	ARGUS	0.05	M
80	16.66	0.93	1.54	114.2	ARGUS	-0.15	K
81	16.91	1.14	1.50	-129.1	ARGUS	-0.75	K
82	16.83	0.96	1.80	-119.2	ARGUS	-0.45	K

Star	R	R-I	B-R	Vr	co	[Fe/H]	ST
83	16.27	1.56	1.33	-53.0	ARGUS	-1.90	M
84	16.89	1.24	1.87	37.8	ARGUS	-0.95	K
85	16.44	0.90	1.11	3.7	ARGUS	0.65	K
86	15.63	0.90	1.31	53.1	ARGUS	-1.05	K
87	15.50	1.14	1.82	-37.2	ARGUS	-0.75	K
88	16.45	0.93	1.37	-87.3	ARGUS	-0.70	K
89	16.63	1.01	1.57	-89.6	ARGUS	-0.95	K
90	16.46	0.97	1.11	52.8	ARGUS	0.05	K
91	15.88	0.93	1.53	-13.8	ARGUS	0.15	K
92	16.53	0.88	1.37	-45.9	ARGUS	0.15	K
93	15.95	1.02	1.98	-54.0	ARGUS	-0.95	K
94	15.93	1.29	1.54	-49.2	ARGUS	-0.05	K
95	16.21	1.05	1.48	-44.8	ARGUS	0.05	K
96	15.94	1.79	2.28	92.7	ARGUS	-0.15	M
97	16.18	1.26	1.98	7.1	ARGUS	0.65	K
98	16.53	1.00	1.63	68.7	ARGUS	0.15	K
99	16.70	1.13	1.33	149.1	ARGUS	-1.90	K
100	16.37	0.99	1.20	-84.6	ARGUS	-0.15	K
101	16.51	0.97	1.32	112.4	ARGUS	-0.55	K
102	16.87	1.04	1.43	29.8	ARGUS	0.55	K
103	16.69	0.89	1.13	-49.7	ARGUS	-1.25	K
104	17.06	1.13	1.99	124.6	ARGUS	-0.65	K
105	15.64	1.14	1.55	64.8	ARGUS	0.25	K
106	16.35	1.79	1.45	2.0	ARGUS	1.05	M
107	16.12	0.95	1.57	56.2	ARGUS	-1.90	K
108	16.65	0.87	1.21	-120.4	ARGUS	-0.75	K
109	15.86	1.16	2.13	23.1	ARGUS	-0.15	K
110	16.42	0.87	1.61	60.4	ARGUS	-0.55	K
111	15.50	1.14	1.82	-45.5	ARGUS	-0.85	K
112	16.01	0.87	1.52	-2.1	ARGUS	-0.65	K
113	15.95	1.23	1.80	-5.3	ARGUS	-0.35	K
114	15.56	1.70	1.98	-65.9	ARGUS	-0.75	M
115	16.85	0.94	1.39	-85.3	ARGUS	0.15	K
116	16.47	0.89	1.88	140.1	ARGUS	0.15	K
117	16.24	1.02	1.91	81.1	ARGUS	-0.05	K
118	16.63	0.86	1.18	-161.1	ARGUS	-1.25	K
119	16.71	0.96	1.47	-87.6	ARGUS	0.25	K
120	16.94	1.05	1.66	66.0	ARGUS	-0.05	K
1306	16.02	1.20	1.44	-92.1	MXAPM	-0.05	K
1318	13.97	1.27	1.93	18.0	MXAPM	-0.65	M?
1320	15.42	0.93	1.30	94.6	MXAPM	0.35	K
1325	15.46	0.91	2.19	-33.9	MXAPM	-1.35	K
1326	14.75	1.02	1.75	-186.2	MXAPM	-1.90	K
1333	15.95	0.87	1.80	156.5	MXAPM	-0.95	K
1335	15.52	1.04	1.83	35.0	MXAPM	-1.15	K
1337	15.56	1.01	1.84	78.5	MXAPM	-0.95	K
1341	15.42	1.28	2.11	-24.3	MXAPM	-0.85	K
1343	16.65	1.08	1.86	-33.2	MXAPM	0.05	K
1347	15.53	1.12	1.90	30.0	MXAPM	-0.45	K
1348	15.77	0.84	1.63	11.8	MXAPM	-0.75	K
1350	15.12	0.92	1.60	38.1	MXAPM	-0.25	K

Star	R	R-I	B-R	Vr	co	[Fe/H]	ST
1352	14.16	0.81	2.09	-88.8	MXAPM	-1.45	K
1359	15.86	1.16	2.13	-3.8	MXAPM	...	K
6108	14.63	1.01	1.01	-26.7	MXAPM	1.15	K
6114	0.00	0.00	0.00	162.1	MXIRIS	-0.75	K
6120	16.13	0.85	1.41	88.6	MXAPM	-0.05	K
6121	15.89	1.00	1.31	60.4	MXAPM	0.05	K
6127	0.00	0.00	0.00	-68.5	MXAPM	1.15	K
6128	16.33	1.16	1.87	34.1	MXAPM	-0.55	K
6132	14.62	0.02	1.45	-100.0	MXAPM	-1.45	K
6135	16.44	1.00	1.59	14.0	MXAPM	-1.05	K
6137	15.87	1.32	1.08	7.9	MXAPM	0.85	M?
6139	16.22	1.10	2.09	-81.1	MXAPM	-1.15	K
6140	16.52	1.01	1.95	-57.6	MXAPM	-1.70	K
6143	16.01	2.27	1.59	-42.1	MXAPM	-1.15	K
6145	16.02	1.07	1.93	-4.0	MXAPM	...	K
6147	16.65	0.95	1.85	45.8	MXAPM	-0.05	K
6152	14.89	1.19	1.28	-78.8	MXAPM	-0.05	K
6153	15.20	1.32	1.97	10.2	MXAPM	-0.85	K
6155	14.89	1.07	1.42	-81.2	MXAPM	-0.85	K
6161	14.73	1.31	1.90	-57.2	MXAPM	-0.85	K
6164	15.89	1.06	1.98	-35.9	MXAPM	-0.85	K
6168	0.00	0.00	0.00	-40.9	MXAPM	...	K
909	16.65	0.95	1.75	46.8	MXAPM	-0.55	K
910	0.00	0.00	0.00	-134.9	MXIRIS	...	K
911	15.66	0.92	1.91	-34.3	MXAPM	-1.25	K
916	15.97	0.99	1.89	76.8	MXAPM	-1.25	K
917	13.48	0.84	1.05	10.3	MX2KCCD	-0.85	K
920	14.78	1.31	1.90	-113.1	MXAPM	-0.45	K
923	16.32	1.18	1.97	-94.7	MXAPM	-1.05	K
924	16.20	0.92	1.10	153.8	MX2KCCD	-0.95	K
928	15.53	0.85	1.66	-21.4	MXAPM	-1.75	K
936	15.56	1.06	1.85	-150.5	MXAPM	-1.05	K
937	16.90	1.08	1.85	11.1	MXAPM	-0.55	K
938	13.45	0.85	0.55	-29.5	MXAPM	1.15	K
939	15.49	1.10	1.44	112.3	MXAPM	-1.05	K
941	14.57	1.25	1.88	1.0	MXAPM	-0.55	K
943	15.68	1.22	1.35	-335.7	MX2KCCD	-1.90	K
945	15.95	1.32	1.45	-21.1	MXAPM	-0.45	K
946	15.71	0.92	2.26	139.7	MXAPM	-1.70	K
948	15.62	1.14	1.82	31.1	MXAPM	-1.90	K
950	16.23	1.09	1.56	-151.3	MXAPM	-1.90	K
951	16.70	1.11	1.60	57.7	MXAPM	-0.95	K
957	15.64	1.18	1.66	-78.7	MXAPM	-1.55	K
960	15.67	1.14	1.28	-73.0	MXAPM	-1.55	K
964	16.02	1.33	2.25	-68.6	MXAPM	-0.85	M?
2001	16.02	1.33	2.15	-26.0	MMTAPM	-1.35	M
2002	15.71	2.52	2.13	-21.9	MMTAPM	-1.05	M
2301	15.68	2.37	2.09	-81.9	MMTAPM	-1.15	M
2302	15.85	1.40	1.75	64.5	MMTAPM	-0.65	M
2501	15.49	1.14	1.87	92.8	MMTAPM	-1.35	M
2502	15.51	2.48	2.05	-67.3	MMTAPM	-1.55	K

Star	R	R-I	B-R	Vr	co	[Fe/H]	ST
2701	15.82	1.25	1.83	9.7	MMTAPM	-0.75	K
2702	15.29	1.06	1.81	-54.7	MMTAPM	-0.95	M
2901	15.22	1.15	1.37	-201.1	MMTAPM	-1.70	K
2902	14.74	1.05	1.74	83.7	MMTAPM	-0.85	K
4101	16.58	0.73	1.51	0.8	MMTAPM	-1.45	K
4102	15.97	0.87	1.80	35.9	MMTAPM	-1.25	K
4301	16.67	0.86	1.18	59.7	MMTIRIS	0.65	M
4302	0.00	0.00	0.00	-23.5	MMTIRIS	...	K
4303	0.00	0.00	0.00	-24.9	MMTIRIS	...	K
4501	16.62	1.14	1.55	-113.3	MMTIRIS	-1.55	K
4502	0.00	0.00	0.00	-20.6	MMTIRIS	...	K
4503	0.00	0.00	0.00	-82.3	MMTIRIS	...	K
4701	0.00	0.00	0.00	87.4	MMTIRIS	...	K
4702	0.00	0.00	0.00	141.1	MMTIRIS	...	K
12901	15.36	1.17	2.15	-57.2	MMTAPM	-1.35	K
12902	15.50	1.14	1.82	66.7	MMTAPM	-1.90	K
13101	0.00	0.00	0.00	119.7	MMTAPM	...	K
13103	16.06	0.93	1.78	70.8	MMTAPM	-1.70	K
13301	15.86	1.16	2.13	-138.0	MMTAPM	-1.35	K
13701	13.81	0.67	0.55	165.9	MMTAPM	1.15	K
13901	16.22	3.04	2.23	-49.1	MMTAPM	-1.55	K
1983	0.00	0.00	0.00	22.4	RETIRIS	...	K
1992	0.00	0.00	0.00	-162.2	RETIRIS	...	K
1001	0.00	0.00	0.00	-129.2	RETAPM	...	K
1002	0.00	0.00	0.00	4.0	RETAPM	...	M
1003	0.00	0.00	0.00	-95.2	RETAPM	...	M
1990	0.00	0.00	0.00	103.6	RETIRIS	...	K
1991	0.00	0.00	0.00	133.3	RETIRIS	...	K
2656	0.00	0.00	0.00	77.1	RETIRIS	...	K
2664	0.00	0.00	0.00	9.4	RETIRIS	...	K
2608	0.00	0.00	0.00	56.6	RETIRIS	...	K
2644	0.00	0.00	0.00	94.0	RETIRIS	...	K

Table 4.3: KINEMATICS VS METALLICITY IN THE FIELD F588

[Fe/H]	N	mean	err	stddev	err	Comments
....	319	10.8	4.7	84.4	3.3	all stars with Vr
-0.20	194	22.3	5.2	71.9	3.6	K*s with [Fe/H]>-1
-1.75	31	-37.8	20.4	113.5	14.4	3 without phot incl
-1.25	34	9.0	18.0	105.1	12.7	
-0.80	43	18.7	12.4	81.4	8.8	
-0.40	46	10.9	11.4	77.3	8.0	
0.00	49	33.4	9.8	68.7	6.9	
0.40	53	24.5	8.7	63.4	6.2	
....	26	2.8	12.6	64.2	8.9	all M stars
....	12	-35.1	27.0	93.7	19.1	bright (R_apm<13.0)

Finally, column 5 gives $\langle V \rangle / \sigma$, a local measure of the degree of rotational support.

Figure 1 presents the APM color–magnitude and color–color diagrams for a 1×1 degree field. Note that the disk main sequence stars are not very numerous in this field. Disk giants, running in a parallel sequence ~ 1 mag redder than the disk MS, are also few in number in relation to the bulge giants at the faintest and reddest magnitudes. The tip of the bulge RGB is clearly seen at $R = 12.3$. The bulge giants span a wide range of color, much larger than that accounted for the photometric dispersion ($\sigma_{B-R} = 0.2, \sigma_{R-I} = 0.13$) and reddening variations, due to their abundance spread. The expected FWHM of the line of sight depth for this field is 0.40 mags, derived from the spatial density distribution of the bulge projected at 1.5 kpc from the Galactic center.

Figure 3 illustrates a subset of these stars for which spectra were obtained. Some 10 stars selected from IRIS photometry are missing from these diagrams because we do not have accurate photometry. Note that the observed stars cover a wide range in magnitudes and colors. They were selected to study the whole range of abundances present in the field. Even though the sample is not free from systematic errors due to its photometric selection, we are confident that we have not missed any important population in the field. As with any magnitude limited sample, the inclusion of more metal poor stars is favored with respect to the metal rich giants because they are brighter.

Figure 4 shows the combined index $Mg+2Fe$ vs color for the sample stars. Note that the bulge stars appear as a homogeneous group in this figure. A

significant part of the spread at a given color, but not all, is due to the measurement dispersion of the indices themselves. The isoabundance lines from the calibration developed in chapter 2 are plotted as well, showing the intrinsic range of abundance spread for the sample. The population studied here shows a wide range of abundances. Optical and near-IR photometry performed in this field is consistent with this wide abundance range.

4.8. The Metallicity Distribution

The metallicity distribution for the observed giants in F588 is given in figure 5a. There is a wide range of metal abundances in the field. There are very metal poor halo stars, as well as very metal rich bulge giants. Note that the scatter in the metallicity determinations increases for the most metal rich giants, as discussed above. This would artificially widen the metallicity distribution at the metal rich end. Figure 5b shows a generalized histogram, where each bin was plotted as a gaussian of σ equal to the error in the corresponding metallicity, and all the bins were summed together. From chapter 2, the metallicity errors are $\sigma_{[Fe/H]} = 0.15$ for $[Fe/H] \leq -1.0$, and $\sigma_{[Fe/H]} = 0.10[Fe/H] + 0.25$ for $[Fe/H] \geq -1.0$. This figure is a better representation of the real metallicity distribution. The fact that the dispersion increases for the more metal rich stars to $\sigma_{[Fe/H]} = 0.3$ casts doubts on the reality of the values for the most metal rich stars. Indeed, it is not clear whether there are any stars in our sample with $[Fe/H] \geq 0.5$. This metal abundance distribution must be corrected for incompleteness with the aid of multicolor photometry. It does not represent the

Figure 4.3 Color-magnitude and color-color diagrams for the stars with spectra.

Figure 4.4 Combined index $Mg+2Fe$ vs dereddened B-V color for the sample stars. The iso-abundance lines correspond to $[Fe/H] = -1.75, -1.5, -1.0, -0.5$, and 0.0, from bottom to top.

Figure 4.5 Metallicity distribution for the K giants observed in F588. The 2σ errorbars of the abundances are shown. All abundances higher than $[Fe/H] \sim 0.5$ are extrapolations.

real metallicity distribution because we selected the stars uniformly over the whole range occupied by bulge K giants in the color-color and color-magnitude diagrams. We note that the same selection effects would affect the R88 sample in Baade's window. The kinematic evidence discussed below suggests that most of the stars more metal poor than $[\text{Fe}/\text{H}] = -1$ are halo rather than bulge giants.

Excluding possible halo stars (with $[\text{Fe}/\text{H}] \leq -1$), the mean metallicity of the bulge giants observed here is $[\text{Fe}/\text{H}] = -0.3$. This is not the mean metallicity of the bulge at the field F588 because the candidates were selected from photometry, and careful account for the selection effects introduced should be taken into account. This mean abundance could be ~ 0.15 dex lower if we have seriously overestimated the metallicity of the most metal rich giants (we recall that an extrapolation of the calibration was applied for stars more metal rich than ~ 0.3 dex). The abundance of the bulge as function of radius is the subject of further discussion in chapter 7.

4.9. Kinematics *vs* Metallicity

Figure 6 shows the final combined index $\text{Mg}+2\text{Fe}$ *vs* observed radial velocities for the program stars. A clear trend is seen, in the sense that the stars with the stronger lines have lower velocity dispersions and higher mean velocities. In figures 7 a to c we plot the radial velocities *vs* the spectroscopic indices Mg , $\text{Fe}5270$ and $\text{Fe}5335$. The same trends are seen in the data.

Figure 8 presents the dependence of velocity on apparent magnitude. It is clear that stars fainter than $R=12.3$ are indeed a homogeneous population, while

Figure 4.6 Measured heliocentric radial velocity *vs* combined index $Mg+2Fe$ for the sample stars.

Figure 4.7 Dependence of heliocentric velocity on line index for Mg (a), Fe5250 (b), and Fe5335 (c).

Figure 4.8 Dependence of heliocentric velocity on apparent magnitude.

the brightest stars belong to the old disk. Inspection of figures 2 and 3 reveals that the great majority of the sample are bulge giants.

Figure 9 shows the radial velocities vs abundances for the program stars. We identify 2 different groups: stars more metal poor than $[Fe/H] = -1$ are associated with the halo, having smaller mean velocities and larger velocity dispersions, while the more metal rich stars belong to the bulge, with larger mean velocity and smaller velocity dispersions. The velocity dispersions of these halo and bulge sample differ by more than 3σ , while the mean line of sight velocities differ by more than 2σ . These are clearly two distinct populations, consistent with the findings of Morrison & Harding (1993) in another field at 2 kpc from the Galactic center. This conclusion stands independently of the calibration of metal abundance, as shown by figures 6 and 7.

The K giant sample is divided into bins according to metallicity. Figure 10 illustrates the run of mean Galactocentric velocity and velocity dispersion for the K giants as function of metal abundance. Each of the bins has about 60 stars, except the most metal poor with only 40 stars. For the 3 most metal rich bins, which we identify with bulge giants, it is evident that the relative importance of rotation with respect to velocity dispersion increases with increasing abundance. This is interpreted as a signature of dissipational collapse. Different selection of bin sizes does not affect these conclusions. The sample is not big enough to decide if there is a smooth transition between halo and bulge stars, although the separation between these systems is quite clear. The most metal rich bins could be relatively more contaminated by the presence of foreground disk stars.

Figure 4.9 Heliocentric radial velocities vs final abundances for the program stars.

Figure 4.10 Run of mean Galactocentric velocity and velocity dispersion for the K giants as function of metal abundance.

Figure 4.11 Run of $\langle V \rangle / \sigma$ vs $[Fe/H]$ for all the stars observed in field F588.

However, from the color–color and color–magnitude diagrams it is estimated that disk contamination is unimportant, less than $\sim 5\%$ of our sample are disk giants.

Figure 11 shows the "local" V_r/σ as function of metallicity, illustrating the relative importance of bulk rotation relative to random motions of stars in the field F588. The more metal poor stars are kinematically hotter than the more metal rich ones. This is seen even if we consider only stars with $[\text{Fe}/\text{H}] \geq -1.0$, excluding the giants that we would associate with the halo. Again the effect is interpreted as a signature of dissipational collapse, as expected if the formation of the bulge was a rapid process, lasting ≤ 1 Gyr, as described by Matteucci & Brocato (1990).

Rather than assume gaussian distributions in velocities to determine if the differences are significant (like Rich 1990), or trimming the outliers (like Morrison et al. 1990), we use Monte–Carlo simulations (like Norris 1986 and Norris & Ryan 1991). The reasons are: 1) the velocity distributions need not be gaussian in nature, and 2) the outliers could be representative. However, given the uncertainties in the relative numbers of stars belonging to the different Galactic components (thin disk, thick disk and halo), we chose not to simulate these components but to analyze how often one expects such trends with metallicity just by chance.

Figure 4.12 Velocity distributions for different metallicity bins.

Thus, to determine the statistical significance of the $\langle V \rangle, \sigma$ vs $[\text{Fe}/\text{H}]$ trends for the bulge giants, we have selected randomly 4 groups of ~ 50 stars each from all the stars with $[\text{Fe}/\text{H}] \geq -1.0$, chosen to simulate the bulge bins plotted in figures 4 to 6. Labeling the groups 1 to 4 arbitrarily to represent increasing metallicity bins, 4.3% of the time the 4 groups are ordered by decreasing $[\text{Fe}/\text{H}]$ and increasing σ . Thus, although the appearance of figure 10a looks very suggestive, it is not impossible that an ordered configuration arises just by chance.

A much more restrictive constraint is placed by dividing the bulge sample into two bins, metal poor and metal rich. It is seen that the metal poor group has smaller mean velocity by 2σ , and larger velocity dispersion by 2.5σ , than the metal rich bin. An F test applied to these 2 groups indicate that the differences are significant to the 2% level. However, repeating the random drawing of stars in two bins on 10^6 trials, the respective mean velocities and velocity dispersions for these 2 groups show differences as large as observed only 0.024% of the times. These probabilities prove that the dependence of kinematics on metallicity is significant to an extremely high confidence level (99.976%).

Finally, figure 12 shows the velocity distributions for different metallicity ranges. No clear structure is seen, in the sense that there are no distinct peaks that we could associate to the disk for example.

4.10. The Halo Contamination

The underlying assumption in running these tests is that the stars tested belong all to the bulge itself, with the contamination by the other Galactic

components such as the Halo or Disk being negligible. The effect of the Halo contamination is estimated to be not very significant, mostly because we have selected out the metal poor stars, and only a possible high metallicity tail of the halo population might be included. We test this possibility by adding at random stars drawn from the metal poor sample ($[\text{Fe}/\text{H}] \leq -1$) to the bulge sample, and repeating the tests. It is found that more than 30 % of the stars in the low metallicity bulge group have to belong to the halo for the effects on the mean velocity and velocity dispersions to be noticeable. Conversely, we have added at random stars drawn from a disk distribution predicted by Lewis & Freeman (1990) to the high metallicity bulge group. Again, there have to be more than 40 % of disk stars included in that group for the effect to be important.

4.11. The Thick Disk Contamination

The question of whether the thick disk would be a major contributor to the number of K giants observed can be estimated using the relative numbers of metal poor thick disk ($mptkd$) and halo giants in the Solar neighborhood. The thick disk is assumed here to have scale-height $H_z = 1$ kpc, and a scale-length of $H_r = 3.5$ kpc. The thick disk can have stars as metal poor as $[\text{Fe}/\text{H}] = -1.6$ (e.g. Morrison, Flynn & Freeman 1989), and no more metal rich than $[\text{Fe}/\text{H}] = -0.3$ (e.g. Norris & Green 1991, Croswell et al. 1992). Morrison (1993) finds this ratio to be $N_{mptkd}/N_{halo} = 2$. Assuming a halo density law as $r^{-3.5}$, and an exponential thick disk with scale length $H_r = 3.5$ kpc, and scale height $H_z = 1$ kpc, we can compute this ratio as function of Galactocentric distance. At the

tangent point of field F588 we find $N_{mptkd}/N_{halo} = 0.007$. Clearly, the metal poor halo stars greatly outnumber the metal poor thick disk giants in the inner regions. Therefore, the most metal poor bins of figures 10 and 11 represent the halo rather than the thick disk. It is important to note here that this conclusion will not change for any other reasonable choices of H_r and H_z , since always the power law will supercede the exponential towards the center.

By analogy, we argue that the ratio of thick disk stars to bulge stars in the region where their metal abundances overlap is not important. This is because in all the fields studied the bulge giants outnumber the halo giants, which in turn have been demonstrated to be more numerous than the metal poor thick disk giants.

The halo accounts for $\sim 20\%$ of the giants in field F588. The total number of thick disk giants with respect to halo giants in the Solar neighborhood is 52. Using these two pieces of information and the density laws described above we estimate that the bulge giants outnumber the thick disk giants by 50 to 1 in F588.

4.12. The Disk Contamination

Not all the stars seen within the selected magnitude and color limits are true bulge giants. The possibility of contamination by disk or halo stars must be considered. As discussed above, the halo stars are easy to separate in view of their very different metallicities and kinematics. On the other hand, the stars from the disk are not so easy to account for. They can be nearby dwarfs, or distant giants.

The nearby K and M dwarfs are expected to be too small in number to be a problem. They would have strong Mg absorption, a small, positive mean velocity with respect to the Sun ($V_m \leq 10 \text{ km s}^{-1}$), and a small velocity dispersion $\sigma = 30 \text{ km s}^{-1}$ (e.g. Wielen 1977). In any case, the strong Mg absorption of K and M dwarfs will determine that only the most metal rich bin is affected by them.

Another argument to support the absence of significant number of dwarfs in our sample is given by the near-IR photometry. The field dwarf sequence is ~ 0.2 magnitudes bluer at J-K than the giant sequence, for the whole range of temperatures considered here (e.g. Frogel & Whitford 1987, their figure 2). In particular, dwarf colors rarely exceed $(J-K)_0 = 1.0$. The near-IR CMD of F588 (figure 2) shows no distinct dwarf sequence present for the range of magnitudes covered by the spectroscopy candidate selection. Similarly, the J-H vs H-K color-color diagram shows that the dwarfs occupy the region with $(J-H)_0 \leq 0.75$, and $(H-K)_0 \leq 0.20$ (e.g. Frogel & Whitford 1987, their figure 3). The near-IR color-color diagram for F588 (figure 2) shows that dwarfs are not present in our sample, for the range of magnitudes and colors considered. This color-color diagram shows a portion of the total field ($5 \times 5 \text{ arcmin}$), where the reddening can be assumed to be constant.

The distant giants must be less numerous than the number of giants at BW, because this field is at a higher latitude. For a scale-height of the inner disk of $h_z = 300 \text{ pc}$ (Freeman 1987), the number of disk giants with respect bulge giants in BW is $N_{F588}/N_{BW} = 0.05$. The absolute number of disk giants towards these low latitude fields can be estimated using a Galactic model (Appendix 1).

However, there are many assumptions involved in constructing such a model, and the answer is not really well constrained. For the moment, we prefer the following approach. We count the number of stars within our color selection, but brighter than the bulge AGB tip, to extrapolate into the bulge giant region. This estimate accounts for both nearby dwarfs and distant giants. Moreover, we know that for these brighter stars $\langle V \rangle = -22 \pm 22$ and $\sigma = 80 \pm 16$ km s⁻¹ from the spectra of 13 stars with $R \leq 15$, most of them being K type stars, with the exceptions being 2 M stars and 1 early type (A) star. These values are uncertain because of the small number of stars.

The near-IR CMD also helps to determine the percentage of disk giants in our sample. Figure 2 shows the mean locus of the disk giants taken from Bessell et al. (1991). Indeed very few stars lie in the disk giant region. In contrast, for the field F589 at $l, b = (12, 3)$ studied in chapter 6, the IR CMD shows a clear disk giant sequence following the line plotted in figure 2. In summary, from the IR-CMD we conclude that the relative number of disk to bulge giants in F588 is 2/40.

The more metal rich bin is the most influenced by disk contamination, as the distant disk giants are expected to be metal rich, because of the well known metallicity gradient in the Galactic disk (Janes 1978). In any event, towards the bulge the more metal rich giants seem to be more rotationally supported, as are the IRAS sources (Miras, OH-IR stars), and it seems natural to associate these groups together.

The disk/bulge giant ratio is expected to be a function of apparent magnitude, because of the different relative distances of the two populations.

This ratio is uncertain, and most bulge studies assume that bulge giants dominate (e.g. Terndrup 1988, Blanco & Terndrup 1990, Rich 1988, etc). However, recently Ruelas-Mayorga & Teague (1992) proposed that the disk giants dominate for the brightest magnitudes at BW, and as a consequence in most bulge fields. This conclusion is driven by their use of a short radial scale-length for the Galactic disk ($h_r = 2$ kpc), and in combination with a long distance to the Galactic center ($R_0 = 8.5$ kpc). The use of more reasonable values ($h_r = 3.5$ kpc and $R_0 = 8.0$ kpc) will alleviate the problem.

Lets now evaluate the disk giant and dwarf contamination issue in terms of the kinematic evidence. First, if our sample included large numbers of nearby disk dwarfs, these would appear to be metal rich, and have local disk kinematics ($\sigma \sim 30$ km s⁻¹, $\langle V \rangle \leq 10$ km s⁻¹). Again, the most metal rich bins in the present sample do not reflect these numbers, the observed velocity dispersion is smaller, and the mean velocity is much larger than that.

Second, if our sample includes significant numbers of disk giants, these should be metal rich and have the kinematics observed by Lewis & Freeman (1990). Thus, the most metal rich bin in the present sample would be the most affected. From table V in Lewis & Freeman (1989), we can integrate the disk kinematics along the line of sight, assuming a shape for the disk velocity ellipsoid. The local old disk velocity ellipsoid has axis ratios $\sigma_u : \sigma_v : \sigma_w = 1.86 : 1.29 : 1.00$ (Janes 1975, in agreement with more recent determinations as discussed by Norris & Ryan 1991). On the other hand, from tables V and VII of Lewis & Freeman (1989) we see that $\sigma_r/\sigma_\phi \sim 1.0 \pm 0.1$ inside the Solar circle. For

simplicity, we assume a constant shape for the velocity ellipsoid of the old disk. Clearly, this axis ratio is a major source of uncertainty for the comparison of bulge and disk kinematics in the inner Galaxy.

Integrating the disk kinematics of Lewis & Freeman (1989) along the line of sight would give an observed velocity dispersion $\sigma = 77$ and 55 km s^{-1} for constant $\sigma_r/\sigma_\phi = 1.0$ and 1.4 , respectively, as well as high mean velocity $\langle V_{los} \rangle \sim 122 \text{ km s}^{-1}$ for the disk in this field. Even though the most metal rich bin has a velocity dispersion of 62 km s^{-1} , the observed mean velocity $\langle V \rangle = 70 \text{ km s}^{-1}$ rules out a significant contribution from disk giants.

Finally, one can use the stars brighter than the tip of the bulge giant branch (those with $R \leq 12.3$), and assume that whatever the population contaminating our sample should share the same kinematics uniformly for the fainter magnitudes. Again, these bright stars with $\sigma = 80 \text{ km s}^{-1}$ and $\langle V \rangle = -22 \text{ km s}^{-1}$ do not appear to be present in great numbers in our higher metallicity bins, which have smaller σ and larger $\langle V \rangle$.

To summarize this section, the presence of large numbers of disk giants contaminating our sample can be ruled out. Therefore, in the following analysis we have not attempted to correct for the effect of the disk contamination. However, a precise estimate of the effect of disk contamination is difficult to make due to the uncertain disk kinematics in the inner Galaxy ($R \leq 3 \text{ kpc}$). A study of a low latitude field with significant numbers disk stars is badly needed. The field at $l, b = (12, 3)$ studied in chapter 6 is ideal in this respect. Determination of a large number of radial velocities and metallicities for giants in this field will help to decide on the real importance of the disk.

4.13. The 1st Moment of the Boltzmann Equation

Kent (1992) models the Galactic bulge as an oblate isotropic rotator with constant $M/L = 1$. This simple model seems to fit very well the available kinematic data (see deZeeuw 1993), except for that Morrison & Harding (1993) measure a mean V_{los} too high in their field at $l, b = (-10, -10)$.

Recent galaxy formation simulations by Katz (1992) show that, depending on when star formation occurs during the formative collapse, bulges could be either oblate rotators or could be flattened by velocity anisotropies.

Kent (1992) finds that the bulge has an axis ratio of 0.61 from $2.4 \mu m$ data. Kent (1992) and Kent et al. (1991) showed that the disk contamination amounts to 40% of the observed integrated light at low latitudes.

Following Rich (1990), we use the first moment of the Boltzmann equation in spherical coordinates to compare different populations. We do not use the first moment of the Boltzmann equation to prove anything, it is just a consistency argument. From Hartwick & Sargent (1978):

$$G M(r)/r = V_c^2 = -\sigma_r^2 d\ln(\rho)/d\ln r - \sigma_r^2 d\ln(\sigma_r^2)/d\ln r + \sigma_r^2(\lambda - 2) + V_{rot}^2$$

where $V_c = (GM/r)^{1/2}$ is the circular velocity, $\lambda = (\sigma_\phi + \sigma_\theta)/\sigma_r$, and V_{rot} is the rotation velocity. Obviously, the circular velocity is constant for the populations of different metallicity at a given distance r , depending only on the enclosed mass. Assuming power law dependences for ρ and σ_r (e.g. Appendix 1) this equation translates to:

$$V_c^2 = (\nu + 2m - 2)\sigma_r^2 + 2\sigma_t^2 + V_{rot}^2$$

where $m = -d\ln(\sigma_r)/dr$, $\nu = -d\ln(\rho)/dr$.

We first test its application to the halo. For that, we have to know ν and m . We will use the kinematic data published for the Baade's window field at $r = 0.5$ kpc, compared with our data at F588 at a distance $r = 1.5$ kpc. The mean velocity and velocity dispersion for the halo at Baade's window are derived from the data of Rich (1990) but making the division at $[\text{Fe}/\text{H}] = -1.0$, as we found this is the transition point between the bulge and halo at our field F588. This procedure is valid as long as there is not a strong metallicity gradient in the halo itself inside 1.5 kpc, otherwise the division has to be made at higher metallicity. For a mean halo difference of 0.3 dex between F588 and BW, the division should be made at $[\text{Fe}/\text{H}] = -0.7$. We recall that there is a metallicity gradient in the bulge itself, that would make the giants at BW more metal rich in the mean than at F588. This means that it would be easier to separate halo from bulge giants in the innermost fields by using metallicities.

For the metal poor subsample at BW, consisting of 11 stars with $[\text{Fe}/\text{H}] \leq -1.0$, the observed mean velocity and velocity dispersions are: $\langle V \rangle = 8.4 \pm 41.4$, and $\sigma = 137 \pm 29$, respectively. For the metal rich subsample at BW, consisting of 42 giants with $[\text{Fe}/\text{H}] \geq -1.0$, these values are $\langle V \rangle = -25 \pm 14$, and $\sigma = 96 \pm 10$, respectively. These values are to be compared with the quantities for F588 listed in table 3. We note that the RRLyr variables at BW have $\sigma = 130 \pm 19$ (Gratton 1987, Tyson 1991), and a mean $[\text{Fe}/\text{H}] = -1.0$ (Walker & Terndrup 1991),

consistent with halo kinematics and abundances. Thus, we adopt for the halo at Baade's window $\sigma = 133 \pm 19$. This value is also consistent with the anisotropic models of Frenk & White (1982) applied to the system of globular clusters. The RRLyr in the halo are distributed according to a $r^{-3.0}$ density law (Oort & Plaut 1975, Saha 1985). The halo light follows a $r^{-3.5}$ law, according to deVaucouleurs and Pence (1978). The blue horizontal branch stars in the halo follow a $r^{-3.2}$ law. Thus, we adopt the average of these values for the halo, $\nu = 3.2$. We will see that the computed values of mean velocity and velocity dispersions used in the Boltzmann equation prove that this law can be extended inwards.

Also, Suntzeff et al. (1991) discussed that for the old populations such as globular clusters, the probability of formation of metal poor RRLyr is much higher than for metal rich ones (at a ratio of about 50:1). For the fields studied in this dissertation, the bulge outnumbers the halo giants by a factor of 5–10. Thus, still the halo RRLyraes should be more numerous than the metal rich, true bulge RRLyraes. It thus seems natural to associate the RRLyr at Baade's window with the halo rather than the bulge itself. By comparing the metal poor data in both fields, we find that the velocity dispersion law has an exponent $m \sim 0$. For the metal rich samples, belonging to the bulge, we find $m = 0.35$. The halo rotation is given by $V_{rot} = 1.27V_{los} = 20 \pm 20 \text{ km s}^{-1}$ in field F588 (see also chapter 7).

Finally, the halo in the Solar neighborhood has an anisotropic velocity dispersion tensor $\sigma_r : \sigma_\phi : \sigma_\theta = 145 : 100 : 90$, giving $\lambda \approx 1$ (after the compilations of Ryan & Norris 1993, and Norris & Ryan 1993, see also appendix 1). We assume that this shape is maintained at F588. Then, equation 1 is now:

$$V_c = 133^2(3.2 + 0 + 1 + 20^2/133^2) \text{ km s}^{-1}$$

which predicts $V_c = 200 \text{ km s}^{-1}$ for the halo at F588. The mass inside 1.5 kpc is then $1.38(\pm 0.26) \times 10^{10} M_\odot$. This is consistent with the mass predicted by the M/L constant model of Kent (1992), slightly smaller than the potential of Blanco & Terndrup (1989), and more massive than the model of Bahcall (1986). To recapitulate, this mass enclosed within 1.5 kpc was found by using a single component (the halo) as tracer, which has well determined kinematics from the present work. Masses computed using other bulge tracers require far more assumptions, including the behavior of the flattening *vs* metallicity.

Now we look at the pure bulge sample at F588 (i.e. stars with $[\text{Fe}/\text{H}] \geq -1.0$). The proper motion data available from Spaenhauer et al. (1992) at BW, and from Cudworth (1986) at the field of the globular cluster M22 give a nearly isotropic shape for the bulge velocity ellipsoid (chapter 5). Thus, we adopt $\lambda \approx 1.7$ for the bulge. From above we also have $m = 0.35$, and $V_{\text{rot}} = 1.27V_{\text{los}}$. The observations give $V_{\text{los}} = 67 \pm 5$, and $\sigma_{\text{los}} \approx \sigma_r = 71 \pm 4 \text{ km s}^{-1}$ for the bulge giants. For $V_c = 200 \text{ km s}^{-1}$ equation 1 predicts $\nu = 6$, which is steeper than the observed radial density dependence of all bulge tracers, which follow $\nu = 3.5\text{--}4.5$ (e.g. Frogel 1988). Similar results are obtained by Rich (1990), even though at that time the halo kinematics in the inner kiloparsecs were not well defined. Changing λ within reasonable limits does not change this conclusion. Adopting slightly different rotation and velocity dispersions within the observed uncertainties does not change this value of ν by more than 0.5. Thus, equation

1 tells us that the bulge must be significantly flattened, and the assumption of spherical symmetry does not apply, giving further evidence that the bulge and halo are different components coexisting in the inner Galaxy. Kent (1992) noted similar inconsistencies in the kinematics derived from bulge tracers.

4.14. The M Giants

The kinematics of 26 M giants observed in the field are consistent with them being bulge members. Their mean Galactocentric velocity is $V_G = 48 \pm 13$ km s⁻¹, and the mean velocity dispersion is $\sigma = 63 \pm 9$ km s⁻¹. Although their number is small and [Fe/H] uncertain, they appear to follow the bulk of the bulge population, rather than the extremely metal rich tail. This is because the most metal rich giants, with $[\text{Fe}/\text{H}] \geq 0$, are fainter on average than our faint magnitude limit, even allowing for the distance spread along the line of sight, and are also redder than the color limit imposed for the selection of the sample. This is clearly illustrated by the color-magnitude diagrams of metal rich globulars studied by Ortolani et al. (1992), and of bulge fields by Udalski et al. (1993). We note that in these globular clusters the K giants reach brighter optical magnitudes than the M giants. This is not to say that there are no very metal rich M giants in our field, just that they are too faint and too red that they have not been included in the spectroscopic sample. In fact, the optical CMD of F588 show the presence of a significant number of such stars in the "descending" red giant branch, much like that of the metal rich globulars. Again, the interpretation of the kinematic properties of the different bulge populations

should be taken with caution unless the abundances are known. It is a mistake to assume that all M giants observed in bulge fields are metal rich when one has magnitude or color-limited samples. Note that clusters like 47 Tuc and M71 at $[\text{Fe}/\text{H}] \sim -0.7$ still have many luminous M giants, which would be present in our sample, while the M giants of the super metal rich cluster Ter 1 (CMD in Ortolani et al. 1992) would have been too faint to be included.

The velocity dispersion of M giants in Baade's window ($\sigma = 113$ km/s, Mould 1983, Sharpless et al. 1991) is slightly larger than the dispersion of the most metal rich bin of the K giants studied by Rich (1990). This is also an indication that not all the M giants are super metal rich, but the kinematics are consistent with the bulk of the M giants having nearly solar abundance.

On the other hand, the IRAS Mira variables (Menzies 1990, Catchpole 1990) and the planetary nebulae (Kinman et al. 1990) in the bulge have lower velocity dispersion and higher rotation. While Minniti et al. (1992) inferred a gradient of about 7 km/s/kpc for the rotation velocity of the K giants, both the Miras and the planetary nebulae give 11 km/s/kpc, indicating that the latter are more metal rich than the K giants in the mean.

4.15. Conclusions

The bulge of the Galaxy is found to be rotating, the mean Galactocentric velocities for fields 588 being 45 ± 10 km s⁻¹. The bulge velocity dispersion decreases with increasing Galactocentric radius, we find $\sigma_{588} = 85 \pm 7$ km s⁻¹, significantly lower than the velocity dispersion at Baade's window, $\sigma_{BW} = 113$

km s⁻¹ (Sharpless et al. 1990, Rich 1990). When dividing the samples into metal rich and metal poor stars, we find a correlation between $[\text{Fe}/\text{H}]$ and σ , in the sense that the metal rich population appears to have a lower velocity dispersion.

The only clear kinematic separation is found at $[\text{Fe}/\text{H}] \sim -1$, and this is interpreted as the separation between the Halo and the bulge components. The velocity dispersions of these 2 populations differ by more than 3σ , and their mean velocities differ by 2σ . For M33, another nearby spiral resolved into stars, Minniti, Olszewski & Rieke (1993) also argued that the halo and bulge of M33 are two separate components.

It is very important to separate true bulge stars from halo stars. These two components seem to be different, with different abundances and kinematics (and possibly ages). Failure to account for halo stars in the bulge leads to a tail in the metallicity distribution, which chemical evolution models have to explain. But closed box model enrichment scenarios can be wrong if the formation of the bulge was separate from the halo.

We define bulge stars in this field as all the stars with $[\text{Fe}/\text{H}] \geq -1$, halo stars all the stars with $[\text{Fe}/\text{H}] \leq -1$ (although it can be argued that some of these stars actually belong to the metal poor thick disk). The disk stars are a minimal contribution to our sample in this field.

The separation between bulge and halo stars is not so straightforward at other fields along the minor axis, such as Baade's window, because the velocity dispersion of the bulge itself increases with decreasing Galactocentric distance, approaching that of the halo, and because we cannot measure the rotation for

the different components. Likewise, a clear separation between the bulge and disk stars in any of these inner fields is not possible, mostly because of our lack of knowledge about what the disk is doing in the inner regions. The pioneering work of Lewis & Freeman (1989) predicts $\sigma_r \sim 100$ km/s at Baade's window, but they do not separate bulge from disk stars.

We confirm the mean rotation and velocity dispersion values for this field published by Minniti et al. (1992) based on a smaller data sample. The mean velocity dispersion for pure bulge giants in this field is given with 6 % error $\sigma_V = 69.8 \pm 4.0$ km/s. Also, we find that the slope of the velocity dispersion law is -0.35 , by combining the present data set with those published at Baade's window. The only other bulge sample that compares with the present in size is that of M giants at BW published by Sharpless et al. (1991). They find significant departure from a gaussian distribution for their radial velocities. The radial velocities for the bulge K giants in F588 have a gaussian distribution.

5. KINEMATICS OF BULGE GIANTS IN THE FIELD OF M22

We report radial velocities, metallicities and near-IR photometry for about 100 giants in the field of the globular cluster M22. Most of them are bulge giants, non-members of the cluster according to proper motions. Dividing the sample according to metallicity, we find that the giants more metal poor than $[\text{Fe}/\text{H}] \approx -1$ have halo-like kinematics, while the metal rich giants have higher rotation and smaller velocity dispersion. The 11 M giants in the field follow bulge rather than halo kinematics. Distances estimated from the optical and IR photometry suggest that the more metal rich giants are much closer on the mean than the metal poor giants (if they had similar ages). It is argued that metal rich giants appear to be closer just because they are younger than the metal poor giants.

5.1. Introduction

Cudworth (1986, hereafter C86) measured proper motions in the field of the globular cluster M22 at $l, b = (9.9, -7.6)$. This field is located at 1.7 kpc projected distance from the Galactic center, where the bulge giants must be the major source of background stars. Indeed, that was one of the reasons to measure proper motions, to separate the M22 giants from the bulge giants. C86 concentrated on the study of the cluster itself. Here we will use his measurements of the background stars to study the bulge.

It is very important to obtain accurate radial velocities, abundances and distances for bulge giant candidates. They will allow for the first time to compute orbits for this stellar component, which in turn will help decide if some high

velocity metal rich stars belong to the bulge (e.g. Grenon 1991). If the bulge is represented in the Solar neighborhood, then a detailed study of chemical composition is possible, which will tell us about the timescale of bulge formation.

The interpretation of the kinematics in the field of M22 is more complicated than field F588 because the selection of bulge giants is different: the magnitude limit $V \sim 15.5$ is brighter, implying that we strongly favor more luminous and closer giants as opposed to distant ones. This magnitude limit was determined mostly by the old blue plates that C86 used for the proper motion determinations. However, having proper motions in this field is an enormous advantage for the study of potential bulge giants.

5.2. Selection of Candidates

Most of the non-cluster stars in the M22 field should be bulge and halo giants, with some minimum contamination from disk giants. The stars of our sample do not belong to the thick disk, because its contribution to the total density along the line of sight is minimal (Appendix 1).

We will use our findings in field F588 as a reference here. Note that other than being in different Galactic quadrants, the relative locations of F588 and M22 with respect to the Galactic center and plane are very similar. Thus, the relative contributions from the different Galactic components should be similar in these 2 fields, as can be seen in figures A6 and A7 of Appendix 1.

The bulge giants in the field of M22 can be seen in the CMDs of C86 and of Alcaïno & Liller (1983). C86 recognized the presence of bulge giants in his

sample. He then used only bright stars ($V \geq 13$) to refer to the absolute proper motion system.

The selection of candidates for the present study is different from that of chapter 4. The objects were selected from C86. All the stars with $(B-V) \geq 0.8$, $V \leq 13$, and cluster membership probability smaller than 99% were in our candidate list. We took spectra of 98 % of that sample, a total of 99 stars. We also included several giants members of M22 in the spectroscopic sample.

The cluster M22 has no published CCD CMD to date, the only published photometry is photographic. These are the BV studies of Cudworth (1986), Alcaïno (1981), Alcaïno & Liller (1983), Arp & Melbourne (1965), and Lee (1979), and the VI study of Lloyd-Evans (1975).

We use the BV photometry of C86 because it is the most recent and it is associated with the proper motion measurements. Figure 1 shows the optical CMD (photometry from C86) for the stars observed. The mean locus of the M22 RGB is also shown.

The data for all the giants of our sample are listed in table 1, and will be discussed in detail in the subsequent sections. In particular, column 1 of Table 1 gives C86 identification number for each star, and columns 2 and 3 give C86 photometry, dereddened using $E(B-V) = 0.32$ (C86).

5.2.1. The IR Photometry

Even though these photographic data are of high quality, we decided to take near-IR frames as an extra check. It is crucial that we be able to separate

Figure 5.1 Optical color magnitude diagram from C86 for the stars with spectra. The solid line shows the locus of the RGB of M22.

Table 5.1
PHOTOMETRY, VELOCITIES, METALLICITIES AND DISTANCES

Star	V	B-V	K	Vr	[Fe/H]	D_V	D_K	Co
86	14.33	1.59	10.58	-298.7	-1.90	8166	11220	K
408	15.13	1.29	12.57	-160.2	-1.90	12303	0	K
467	15.12	1.17	12.86	-138.5	-1.90	8831	0	K
681	14.69	1.56	10.27	-55.5	-1.90	14928	17701	K
385	15.05	1.21	12.53	-30.8	-1.90	9333	0	K
386	14.23	0.89	12.69	-16.9	-1.90	0	0	K
203	15.01	1.23	12.32	-183.0	-1.90	10046	0	K
510	14.16	1.38	11.36	-77.1	-1.90	9290	0	K
292	15.05	1.30	11.99	0.0	-1.55	10046	0	K
383	15.08	1.59	11.87	37.0	-1.45	15488	5861	K
494	13.50	1.25	10.87	31.0	-1.45	3221	0	K
500	13.60	1.65	9.84	-205.5	-1.45	8166	5272	K
637	13.62	1.61	10.02	41.6	-1.35	7211	4853	K
41	14.38	1.52	11.61	-105.9	-1.35	9233	0	K
53	14.11	1.33	11.03	-48.3	-1.35	6053	0	K
392	13.62	1.80	10.11	-72.3	-1.25	8091	3767	K
320	15.41	1.69	13.59	-133.3	-1.25	0	0	K
315	14.97	1.53	11.35	-115.2	-1.25	11749	7656	K
403	14.47	1.40	11.27	11.9	-1.25	7621	3873	K
411	14.64	1.61	10.11	13.2	-1.25	6918	12190	K
610	14.62	1.38	999.00	-34.0	-1.15	7112	0	K
578	14.24	1.48	10.36	-78.6	-1.15	7244	0	K
218	14.84	1.66	999.00	75.5	-1.15	11695	0	K
571	15.49	1.36	12.69	-150.3	-1.05	6516	0	K
690	14.83	1.38	11.76	49.1	-1.05	7211	0	K
703	15.34	1.55	12.04	-32.8	-1.05	12190	5035	K
196	15.10	1.74	10.67	-21.1	-0.95	12823	12246	K
511	14.88	1.68	999.00	-98.2	-0.95	10914	0	K
114	14.75	1.19	12.16	33.9	-0.95	3614	0	K
314	14.79	1.46	999.00	20.8	-0.95	7656	0	K
39	14.26	1.41	10.68	-14.0	-0.85	4920	4365	K
567	15.17	1.33	11.85	-15.1	-0.85	6397	0	K
714	14.52	1.51	10.96	1.7	-0.75	5598	3681	K
18	14.50	1.54	10.72	30.8	-0.75	6607	5346	K
717	14.34	1.72	9.88	-43.8	-0.65	6194	7244	K
6	14.09	1.41	10.73	-17.5	-0.65	3784	0	K
591	14.00	1.10	11.76	-1.9	-0.65	1096	0	K
307	14.89	1.45	11.79	-47.1	-0.65	5998	0	K
36	14.96	1.36	12.60	87.2	-0.65	5082	0	K
303	14.82	1.59	11.08	-28.5	-0.65	4467	5754	K
84	14.67	1.44	11.64	-66.6	-0.65	5297	0	K
721	14.23	1.37	999.00	-5.6	-0.55	3236	0	K
662	14.98	1.29	11.71	-146.1	-0.55	3565	0	K
726	14.43	1.31	11.33	71.8	-0.55	3006	0	K
50	14.65	1.54	10.73	-17.4	-0.55	5702	5754	K
719	14.33	1.52	10.28	7.6	-0.55	4508	5494	K
393	14.54	1.33	11.62	-10.3	-0.45	8872	0	K
140	14.98	1.41	12.40	-16.4	-0.45	4571	0	K
516	14.12	1.35	999.00	-46.0	-0.35	2109	0	K

Star	V	B-V	K	Vr	[Fe/H]	D_V	D_K	Co
607	14.68	1.37	11.54	-8.5	-0.35	2871	0	K
148	14.25	1.68	999.00	53.9	-0.35	5176	0	K
101	14.27	1.52	10.76	117.5	-0.35	3767	3062	K
577	15.22	1.43	11.83	-109.2	-0.35	4634	0	K
689	15.10	1.54	10.84	-59.8	-0.25	5546	8053	K
691	15.26	1.59	11.59	-34.2	-0.25	6761	6792	K
13	15.20	1.52	999.00	38.5	-0.25	5176	0	K
371	15.14	1.27	12.81	-63.2	-0.15	2228	0	K
7	14.73	1.49	10.69	86.3	-0.15	3436	5272	K
156	14.44	1.56	999.00	59.3	-0.15	4055	0	K
279	14.81	1.56	11.07	16.0	-0.15	4592	4246	K
52	14.70	1.49	11.35	-22.0	-0.05	2716	0	K
152	14.98	1.70	999.00	177.8	-0.05	6252	0	K
308	14.71	1.54	10.90	92.3	-0.05	3548	4508	K
29	15.07	1.25	12.27	26.4	-0.05	0	0	K
211	14.31	1.51	10.72	58.7	0.20	2089	3006	K
522	15.24	1.37	12.30	94.5	0.20	1770	0	K
328	15.33	1.45	12.10	-98.2	0.20	2547	0	K
618	14.24	1.38	999.00	18.9	0.20	1117	0	K
231	14.26	1.64	10.31	-11.8	0.20	3516	3597	K
687	14.53	1.01	12.61	6.7	0.20	0	0	K
402	14.92	1.50	10.98	24.4	0.20	2535	4898	K
318	14.94	1.36	12.61	8.1	0.20	1406	0	K
300	14.98	1.20	11.92	53.1	0.20	0	0	K
139	15.13	1.39	12.82	1.7	0.20	1660	0	K
40	15.15	1.29	12.36	-57.9	0.20	0	0	K
588	14.59	0.97	999.00	-13.6	0.20	0	0	K
425	15.13	1.59	11.65	-45.2	0.20	4325	0	K
58	14.51	1.17	12.59	42.2	0.20	0	0	K
275	14.90	1.45	999.00	17.4	-1.90	14454	0	M
33	13.85	1.62	999.00	-124.4	-0.65	2767	0	M
36	13.80	1.70	999.00	-34.0	-0.95	6637	0	M
584	14.84	1.45	9.93	3.8	-1.90	1770	0	M
575	15.06	1.78	9.89	-41.1	-1.90	4716	9376	M
277	14.38	1.63	999.00	-17.3	-0.95	8279	0	M?
410	14.99	1.26	11.76	41.8	0.20	0	0	M
590	14.93	1.68	10.91	50.5	-0.35	7178	6252	M
161	14.90	1.57	999.00	102.3	0.20	3581	0	M
41	13.48	2.02	999.00	8.9	-0.75	6855	0	M
373	14.60	1.64	10.52	20.7	0.20	4074	4550	M?
412	11.66	1.25	9.48	-10.9	0.20	0	0	K
515	13.49	2.00	999.00	-96.3	-0.85	7145	0	K
494	13.50	1.25	10.87	31.0	-1.45	3221	0	K
500	13.60	1.65	9.84	-205.5	-1.45	8166	5272	K
392	13.62	1.80	10.11	-72.3	-1.25	8091	3767	K
637	13.62	1.61	10.02	41.6	-1.35	7211	4853	K
19	13.77	1.91	999.00	-59.7	-0.95	7943	0	K
424	13.81	1.71	9.91	-84.5	-0.05	3784	2729	K
61	13.94	1.93	9.61	47.4	-0.55	7047	5521	K
426	13.98	1.18	999.00	25.6	-0.45	0	0	K
27	13.98	1.18	999.00	38.5	0.20	0	0	K

Star	V	B-V	K	Vr	[Fe/H]	D_V	D_K	Co
274	14.75	0.23	14.37	-266.2	0.20	0	0	M22HB
478	14.47	1.09	12.25	-160.7	-1.90	4508	0	M22
215	12.47	1.43	999.00	-134.8	-1.90	4613	0	M22
12	14.10	0.60	999.00	-196.8	0.20	0	0	M22HB
720	13.72	1.13	999.00	-166.6	-1.90	3908	0	M22
574	14.45	0.42	13.29	-136.3	0.20	0	0	M22HB
85	14.06	1.13	11.40	-109.8	-1.90	4550	0	M22
55	13.12	1.27	10.16	-141.8	-1.90	4405	0	M22
367	13.79	1.03	999.00	-223.8	0.20	0	0	M22
555	12.17	1.36	999.00	-162.0	0.20	431	0	M22
572	0.00	0.00	13.29	-112.9	0.20	0	0	M22
42	99.99	9999.00	999.00	-97.5	-1.90	0	0	M22

clearly the cluster members from the non-members. The proper motions of C86 suffice in most cases, but when in doubt we need an extra check. Due to the high radial velocity of M22 ($V_{M22} = -160 \text{ km s}^{-1}$, from chapter 2), if we include M22 members in the bulge sample the results will be biased. The same is true if we exclude bulge giants by mistakenly associating them with the cluster. Also, the deep IR frames allow us to assess the crowding; the presence of fainter nearby companions could bias the determination of some proper motions.

The observations were taken on the nights of June 18 and 19 1991 at the Steward 90" telescope, with the Nicmos3 256×256 array camera. Unfortunately, the whole field could not be mapped with the array. A field of 12.5×10.5 arcmin was covered with the J and K filters, covering more than half of the stars with spectra. The exposure times were 12 and 15 seconds per frame in K and J, respectively. The data were taken on strips in declination, with 2/3 of a single frame overlapping with the next one. A total of 5 strips were observed, centered on the cluster M22. The brighter cluster giants are saturated in both J and K, the exposure times were chosen not to study the cluster itself but the underlying bulge population.

In general, the stars with measured proper motions are relatively isolated. The means that aperture photometry should give good measurements. We chose apertures of 3 pixels radius, and the sky was measured in an annulus from 10 to 15 pixels away from the center of the stars. DAOPHOT photometry was also obtained, but those data will be reported elsewhere. The photometric reductions do not differ from those described in chapter 3, and we will not discuss them

further here. The photometric errors are: $\sigma = 0.05, 0.10$, and 0.20 for $K = 12, 13.5$, and 14.5 , respectively. The IR observations were dereddened adopting $E(B-V) = 0.32$ for M22 (C86), and the reddening relations: $E(J-K) = 0.56 E(B-V)$, $E(V-K) = 3.2 E(B-V)$, and $A_K = 0.346 E(B-V)$ (Rieke & Lebofski 1983).

The K magnitudes and $V-K$ colors are listed in Table 1, columns 4 and 5. Figure 2 presents the $K, V-K$ CMD for all the stars with spectra and IR photometry. The locus of the RGB of M22 is shown. The $V-K$ colors were computed using the V magnitudes given by C86. The photometric errors in the V magnitudes are $\sigma = 0.05$ (c.f. C86).

5.3. The Spectroscopy

5.3.1. The Argus observations:

For a detailed description of the observations at the CTIO 4 m telescope with the multifiber spectrograph Argus see chapter 2. The relative coordinates given by C86 were good enough for the positioning of Argus fibers. They were not as good as the coordinates for other clusters observed (measured at the Grant machine at KPNO), because we had to shift the position of some of the fibers by small amounts, but this was not very time consuming. Two different fiber configurations were observed with Argus in the field of M22, for a total of 45 spectra.

Figure 5.2 Near-IR color magnitude diagram for all the stars for which we have velocities and IR photometry (about 2/3 of the total proper motion sample).

5.3.2. The MMT Red Channel Observations

The observation procedure is very different from that of Argus. We have a long slit (1.5×180 arcsec), which allows the placement of 2–3 stars in a line, after the instrument is rotated appropriately. This procedure was found to be expedient, it is worth it to spend the extra few minutes rotating carefully the instrument to place multiple stars on the slit. The stacking problem at the MMT helped to ensure that the stars fill the slit, and did not spend most of the time on one side of it. In two nights we were able to obtain 70 spectra in the field of M22, despite the fact that the field is at $\delta = -26^\circ$.

At the MMT about a dozen M22 stars were included in the sample, to use as reference to check the radial velocity measurements, to use as standards for the metallicity determinations, but most of all, to ensure a proper discrimination between cluster and bulge stars.

The radial velocities are very helpful to decide on the membership of the stars for which the proper motions predict probabilities higher than 1% but smaller than 98%. Even though our velocities are good only to ~ 10 km/s, the velocity dispersion of the background field is very large, and so membership can be determined quite accurately. In all other cases, the radial velocities confirmed the membership probabilities obtained by C86.

Figure 3 shows the measured radial velocities vs V magnitude for all the stars with spectra. This plot is useful to decide if there is a significant number of disk giants included in the sample. These are expected to be relatively bright and have a small velocity dispersion.

Figure 5.3 Measured radial velocity vs visual magnitude for all the stars with spectra (including some M22 giants).

5.3.3. Metallicities:

The metallicities are derived following the calibration of chapter 2. The indices measured for all the stars in the M22 field are listed in table 2. Figure 4 presents the combined magnesium and iron index *vs* color corrected for reddening. The isoabundance lines from the calibration of chapter 2 are also shown. The M22 giants are indeed metal poor, and they were used to define the metal poor end of the calibration.

Figure 5 shows the metallicity distribution for the bulge giants with $V \geq 14.0$ in the field of M22. The observed bulge giants show a mean abundance of $[\text{Fe}/\text{H}] = -0.65$, but a significant metallicity dispersion is present. Part of this dispersion is due to our measurement errors. We have found that $\sigma_{[\text{Fe}/\text{H}]}$ increases for the most metal rich stars. Compare this figure with the same figure for the field F588. They are very similar, even though the selection of giants was very different. The only difference is that the proportion of metal poor stars (with $[\text{Fe}/\text{H}] \leq -1.0$) is larger in the M22 field than in F588 (figure 6 of chapter 4). In the M22 field, we find that 22 K giants have $[\text{Fe}/\text{H}] \leq -1.0$, *vs* 52 K giants with $[\text{Fe}/\text{H}] \geq -1.0$. This is due to the selection of the sample, we are biased towards picking metal poor giants. Therefore, figure 5 is not the real metallicity distribution of this field; it is incomplete for the metal rich end.

5.4. Distances

Even though the IR photometry covers only a fraction of the total sample, it is also very useful to determine the mean distance of the giants. If there were

Table 5.2 : Spectroscopic Indices

Star	H β	Mg	Mg1	Mg2	Mgb	MgH	Fe492	Fe498	Fe50	Fe52	Fe53	Fe54
86	0.84	0.86	0.72	0.78	0.77	0.55	0.65	0.86	0.79	0.75	0.67	1.19
408	1.26	0.85	0.83	1.16	0.84	0.75	1.06	0.79	0.77	0.75	0.66	0.89
467	0.85	0.79	0.76	1.00	0.79	0.76	0.65	0.95	0.80	0.78	0.80	0.75
681	0.93	0.80	0.69	0.82	0.82	0.60	0.71	0.87	0.76	0.78	0.77	0.94
385	0.86	0.84	0.75	0.67	0.81	0.78	0.75	0.81	0.80	0.81	0.72	0.98
386	0.84	0.84	0.72	0.67	0.79	0.68	0.72	0.81	0.75	0.76	0.71	0.86
203	0.75	0.85	0.73	0.76	0.77	0.72	0.67	0.83	0.77	0.76	0.77	1.06
510	0.76	0.76	0.64	0.57	0.87	0.64	0.70	0.87	0.81	0.81	0.75	1.02
292	0.79	0.80	0.76	0.90	0.88	0.61	0.64	0.83	0.73	0.84	0.82	0.79
383	0.83	0.85	0.71	0.72	0.87	0.60	0.69	0.88	0.82	0.83	0.83	0.95
494	0.75	0.98	0.95	1.20	0.85	0.69	0.69	0.96	0.86	0.86	0.62	0.66
500	0.79	0.93	0.87	1.07	0.85	0.72	0.62	0.88	0.77	0.79	0.81	0.80
637	0.87	0.91	0.88	1.06	0.80	0.74	0.67	0.88	0.84	0.87	0.76	0.79
41	0.77	0.87	0.77	1.02	0.88	0.65	0.62	0.91	0.80	0.83	0.83	0.77
53	0.90	0.92	0.88	1.09	0.82	0.69	0.68	0.95	0.83	0.82	0.75	0.78
392	0.76	1.05	1.03	1.26	0.86	0.84	0.69	1.00	0.87	0.85	0.72	0.65
320	0.77	0.96	0.90	0.88	0.90	0.83	0.69	0.86	0.81	0.81	0.86	1.18
315	1.01	0.85	0.74	0.62	0.86	0.68	0.68	0.99	0.83	0.86	0.84	0.95
403	0.73	0.86	0.80	1.04	0.92	0.64	0.66	0.90	0.79	0.84	0.83	0.77
411	0.90	0.90	0.89	0.90	0.89	0.81	0.65	0.79	0.79	0.85	0.82	0.91
610	0.81	0.92	0.84	0.80	0.81	0.80	0.59	0.83	0.81	0.80	0.82	0.46
578	0.78	0.96	0.87	0.81	0.90	0.84	0.65	0.92	0.80	0.81	0.79	0.99
218	0.91	0.96	1.12	0.81	1.13	1.30	0.23	1.26	1.11	0.87	0.78	0.44
571	0.77	0.94	0.80	0.76	0.92	0.70	0.71	0.85	0.84	0.83	0.78	1.21
690	0.79	0.88	0.78	0.76	0.89	0.74	0.69	0.82	0.82	0.84	0.84	1.01
703	0.85	0.98	0.90	0.92	0.87	0.88	0.57	0.85	0.82	0.80	0.83	0.48
196	0.79	1.07	0.98	0.94	0.94	0.91	0.67	0.86	0.80	0.83	0.79	0.96
511	0.79	0.99	0.87	0.83	0.93	0.77	0.68	0.80	0.81	0.84	0.83	1.13
114	0.80	0.89	0.87	1.06	0.80	0.64	0.69	0.93	0.84	0.85	0.77	0.82
314	0.76	1.02	0.92	0.87	0.89	0.83	0.75	0.84	0.80	0.80	0.77	0.94
39	0.76	0.97	0.85	1.08	0.75	0.76	0.65	0.91	0.82	0.78	0.86	0.81
567	0.83	0.92	0.80	0.75	0.88	0.67	0.71	0.85	0.82	0.82	0.84	1.08
714	0.82	0.98	0.88	0.80	0.88	0.83	0.75	0.81	0.86	0.88	0.80	1.08
18	0.75	1.11	1.11	1.24	0.92	0.90	0.66	1.03	0.87	0.88	0.69	0.69
717	0.78	1.11	1.08	1.02	0.93	1.09	0.52	0.90	0.84	0.81	0.85	1.06
6	0.71	0.97	0.88	1.06	0.81	0.70	0.67	0.90	0.81	0.81	0.86	0.79
591	0.69	0.80	0.70	0.92	0.85	0.59	0.64	0.84	0.76	0.89	0.82	0.78
307	0.81	0.96	0.85	0.84	0.89	0.71	0.71	0.78	0.82	0.85	0.84	1.08
36	0.82	0.98	0.88	1.04	0.76	0.72	0.73	0.87	0.82	0.81	0.83	0.85
303	0.77	1.08	0.99	0.91	0.92	0.92	0.71	0.84	0.80	0.84	0.81	1.02
84	0.80	1.05	0.94	0.89	0.93	0.78	0.69	0.87	0.82	0.83	0.77	1.10
721	0.79	0.94	0.80	0.79	0.91	0.69	0.72	0.87	0.82	0.85	0.85	1.02
662	0.83	1.04	0.90	0.92	0.84	0.71	0.59	0.89	0.83	0.80	0.76	0.34
726	0.76	0.96	0.82	0.82	0.84	0.72	0.74	0.86	0.82	0.86	0.79	0.88
50	0.74	1.04	0.94	1.18	0.80	0.82	0.65	0.88	0.80	0.81	0.86	0.80
719	0.85	0.95	0.95	0.91	0.92	0.95	0.64	0.85	0.82	0.86	0.91	1.04
393	0.82	0.93	0.82	0.72	0.89	0.76	0.74	0.79	0.81	0.86	0.85	1.12
140	0.75	1.02	0.91	1.16	0.83	0.70	0.71	0.97	0.86	0.80	0.86	0.79
516	0.80	1.04	1.01	0.93	0.95	1.02	0.59	0.81	0.82	0.78	0.84	1.08
607	0.75	0.95	0.85	1.05	0.93	0.76	0.66	1.04	0.79	0.84	0.89	0.81

Star	H β	Mg	Mg1	Mg2	Mgb	MgH	Fe492	Fe498	Fe50	Fe52	Fe53	Fe54
148	0.78	1.05	0.99	0.93	0.90	0.97	0.62	0.81	0.79	0.88	0.91	1.00
101	0.70	1.01	0.99	1.20	0.91	0.74	0.64	0.84	0.83	0.88	0.87	0.79
577	0.84	1.22	1.42	0.99	1.27	1.25	0.26	1.08	1.01	0.75	0.74	1.00
689	0.75	1.09	0.98	0.96	0.96	0.95	0.64	0.88	0.84	0.85	0.85	1.14
691	0.79	1.06	0.98	0.90	0.90	0.96	0.73	0.83	0.81	0.87	0.88	1.01
13	0.92	1.06	1.04	1.25	0.94	0.79	0.75	0.99	0.93	0.90	0.82	0.82
371	0.83	1.00	0.88	0.84	0.89	0.76	0.72	0.85	0.81	0.85	0.80	1.06
7	0.84	1.11	1.02	1.19	0.84	0.81	0.67	0.93	0.82	0.83	0.85	0.82
156	0.77	1.04	0.98	0.92	0.90	0.97	0.67	0.81	0.80	0.92	0.87	0.94
279	0.74	1.06	1.07	1.23	0.83	0.86	0.66	0.89	0.81	0.90	0.87	0.81
52	0.75	1.09	0.99	1.19	0.81	0.82	0.70	0.92	0.84	0.83	0.89	0.83
152	0.77	1.14	1.08	0.96	0.95	0.90	0.56	0.86	0.85	0.90	0.90	0.88
308	0.78	1.06	0.95	0.91	0.91	0.81	0.67	0.79	0.80	0.88	0.90	0.99
29	0.78	0.98	0.98	1.12	0.83	0.77	0.61	0.88	0.83	0.86	0.81	0.69
211	0.90	1.10	1.10	1.22	0.90	1.04	0.67	0.92	0.83	0.90	0.86	0.84
522	0.70	1.09	0.99	1.15	0.98	0.79	0.64	0.82	0.78	0.93	0.89	0.85
328	0.65	1.25	1.20	1.49	1.08	0.98	0.55	1.08	0.95	0.90	0.89	0.82
618	0.80	0.95	0.87	0.78	0.90	0.85	0.60	0.84	0.82	0.89	0.92	0.54
231	0.68	1.29	1.24	1.47	1.13	1.08	0.56	0.99	0.89	0.84	0.88	0.80
687	0.86	0.87	0.81	0.73	0.86	0.75	0.71	0.80	0.78	0.84	0.86	0.98
402	0.77	1.14	1.08	1.00	0.93	1.07	0.65	0.87	0.82	0.91	0.83	0.99
318	0.74	0.97	0.94	1.11	0.97	0.81	0.64	0.84	0.83	1.16	0.90	0.84
300	0.97	1.01	0.99	1.11	0.87	0.74	0.69	0.94	0.88	0.83	0.82	0.82
139	0.74	0.97	0.90	1.15	0.94	0.72	0.66	0.87	0.82	0.90	0.89	0.82
40	0.91	1.07	1.05	1.27	0.87	0.80	0.60	0.97	0.85	0.85	0.84	0.85
588	0.86	0.97	1.14	0.83	1.29	1.12	0.27	1.23	1.08	0.84	0.79	0.94
425	0.65	1.15	1.09	1.06	0.88	1.21	0.63	0.80	0.80	0.87	0.90	1.04
58	0.78	0.96	0.83	0.79	0.94	0.70	0.71	0.82	0.80	0.85	0.85	0.99
275	0.90	0.76	1.05	0.61	1.37	1.41	0.23	1.65	1.37	0.82	0.64	0.72
33	0.80	1.19	1.17	1.29	0.85	0.96	0.41	1.02	0.87	0.72	0.82	0.71
36	0.91	1.15	1.40	1.25	1.28	1.47	0.25	1.46	1.20	0.79	0.75	0.60
584	0.90	0.70	0.68	0.73	0.69	0.68	0.66	0.81	0.79	0.76	0.79	0.97
575	0.80	0.78	0.67	0.69	0.80	0.69	0.67	0.80	0.77	0.77	0.78	0.97
277	0.83	1.05	1.13	0.92	1.08	1.12	0.40	1.03	0.95	0.81	0.79	0.92
410	0.76	1.07	1.01	0.98	0.97	0.94	0.51	0.88	0.86	0.84	0.85	1.02
590	0.84	1.12	1.16	1.20	0.95	1.09	0.53	0.92	0.87	0.88	0.85	0.78
161	0.78	1.12	1.02	1.00	0.91	0.92	0.46	0.86	0.84	0.86	0.89	0.55
41	0.76	1.10	1.11	1.24	1.06	1.03	0.48	0.96	0.84	0.90	0.87	0.75
373	0.65	1.16	1.18	1.39	0.88	0.96	0.55	0.92	0.85	0.90	0.89	0.80
412	0.80	1.10	1.08	0.96	1.02	1.15	0.48	0.94	0.90	0.84	0.89	1.11
515	0.77	1.15	1.13	1.01	0.99	1.08	0.53	0.87	0.90	0.80	0.86	1.11
494	0.75	0.98	0.95	1.20	0.85	0.69	0.69	0.96	0.86	0.86	0.62	0.66
500	0.79	0.93	0.87	1.07	0.85	0.72	0.62	0.88	0.77	0.79	0.81	0.80
392	0.76	1.05	1.03	1.26	0.86	0.84	0.69	1.00	0.87	0.85	0.72	0.65
637	0.87	0.91	0.88	1.06	0.80	0.74	0.67	0.88	0.84	0.87	0.76	0.79
19	0.89	1.12	1.09	1.33	0.85	0.89	0.64	0.96	0.86	0.85	0.78	0.78
424	0.71	1.20	1.23	1.40	0.88	1.00	0.58	0.94	0.85	0.86	0.88	0.78
61	0.78	1.14	1.13	1.01	0.98	1.09	0.55	0.90	0.86	0.86	0.89	1.01
426	0.79	0.96	0.86	0.78	0.89	0.74	0.73	0.82	0.80	0.83	0.77	0.94
27	0.82	1.10	1.09	1.31	0.90	0.80	0.72	0.93	0.85	0.91	0.79	0.81
274	1.03	0.78	0.68	0.65	0.75	0.71	0.69	0.77	0.76	0.77	0.81	1.24

Star	H β	Mg	Mg1	Mg2	Mgb	MgH	Fe492	Fe498	Fe50	Fe52	Fe53	Fe54
478	0.82	0.77	0.62	0.63	0.74	0.57	0.75	0.88	0.79	0.69	0.65	0.98
215	0.80	0.80	0.67	0.73	0.80	0.61	0.56	0.78	0.78	0.78	0.78	0.37
12	0.80	0.83	0.73	0.66	0.79	0.71	0.74	0.71	0.78	0.78	0.75	1.22
720	0.83	0.80	0.66	0.69	0.76	0.59	0.66	0.84	0.77	0.74	0.69	1.04
574	1.05	0.75	0.63	0.67	0.75	0.64	0.65	0.79	0.74	0.74	0.75	1.10
85	0.81	0.85	0.74	0.66	0.76	0.72	0.73	0.79	0.78	0.75	0.73	1.05
55	0.80	0.74	0.64	0.65	0.76	0.58	0.67	0.82	0.77	0.76	0.77	1.09
367	0.80	0.97	0.88	0.82	0.86	0.83	0.70	0.87	0.82	0.85	0.84	1.25
555	0.86	1.47	1.85	0.88	1.85	1.15	0.66	0.77	0.89	0.65	0.87	1.65
572	0.85	0.75	0.63	0.66	0.75	0.60	0.61	0.80	0.73	0.75	0.69	0.97
42	0.81	0.79	0.72	0.98	0.88	0.58	0.59	0.90	0.75	0.77	0.79	0.72

Figure 5.4 Combined Magnesium + Iron index *vs* derreddened B-V color. The fiducial abundance lines from bottom to top correspond to $[Fe/H] = -1.75, -1.5, -1.0, -0.5$, and 0.0 . The biggest circles are M22 giants.

Figure 5.5 Metallicity distribution for all the bulge giants measured in the field of M22.

no magnitude limit, most of them should be at the tangent point towards the bulge, located at 7.8 kpc from the Sun. However, the proper motion sample is magnitude limited, and the possible inclusion of thick or thin disk giants would bias this mean distance (as discussed in Appendix 1).

To determine the distances for the bulge giants from the K photometry, we use the IR isochrones published by Bell (1992), complemented at the metal rich end by the results of Bessell et al. (1991). A check is made using the fiducial globular cluster lines given by Frogel, Cohen & Persson (1983, hereafter FCP83). The distances obtained that way were no different than the ones obtained using the Bell (1993) isochrones. The choice of the Bell (1992) isochrones is justified because they fit the cluster 47Tuc very well. We had to use the models of Bessell et al. (1991) because some of the bulge giants have higher metallicity than the range of abundances covered by the Bell isochrones.

The procedure to determine distances from the K photometry (D_K) listed in table 1 is as follows. The metallicity for each star is obtained from the B–V color and the spectroscopic indices. Then, given its $(V-K)_0$ color it is placed in the isochrone of 13 Gyr corresponding to its abundance. Finally, the observed K magnitude compared with the models gives the distance modulus for each star, after correcting for A_K . These distances are estimated to be accurate to 25 % but are not free from systematic errors. We note that using the 10 Gyr isochrones, perhaps a more appropriate choice for the age of the bulge (e.g. Holtzman et al. 1993), the distances would be larger by about 0.3 magnitudes (or 450 and 1200 pc at distances of 3 and 8 kpc, respectively). Unfortunately,

the K photometry gives distances for only $\sim 1/2$ of the sample. In addition, a number of metal rich stars are too blue and yield unreasonably short distances. Luckily, all the stars have BV photometry.

Then, we used also the BV photometry of C86 to obtain another distance estimate for each star. The same procedure is repeated, this time using the isochrones of Bergbush & Vandenberg (1992), as given in their figure 6. We have used this set of isochrones to be consistent with our choice for the IR. Any systematic differences between the two distance estimates then would not be due to the models. The distances from the BV photometry (D_V) are also listed in table 1.

These figures also show that we recover a distance for M22 of 4.0 kpc and 3.9 kpc, from the V and the K photometry, respectively. This distance is larger than $D = 3.2$ kpc published by C86.

The giants non-members of M22 show a large distance spread along the line of sight. There is structure in the distance distribution (figure 6), with 2 broad peaks. A number of giants yield small distances, these are in general the most metal rich stars in the sample. It is difficult to decide if this due to a systematic effect in the determination of distances for metal rich giants, or if these are really lower luminosity, metal rich stars nearby. From the model of Appendix 1 we would argue that there should not be so many metal rich stars nearby, implying that something might be wrong with the distances.

If we plot distances *vs* $[\text{Fe}/\text{H}]$, a strong trend is seen, and 2 distinct groups can be identified (figure 7). The stars with $[\text{Fe}/\text{H}] \leq -0.9$ have a mean distance

Figure 5.6 Distribution of distances for the sample giants.

Figure 5.7 Metal abundances *vs* distances derived from the BV photometry for the sample giants.

consistent with R_0 , and a large range of distances, from about 2 to 20 kpc. These are metal poor halo stars (and maybe some metal poor thick disk giants), and the distance determinations work reasonably well for them. Instead, the more metal rich stars with $[\text{Fe}/\text{H}] \geq -0.9$ have a much smaller mean distance of ~ 4 kpc. The distances computed with the K photometry show the same effect. Some trend with metallicity is expected, because the metal poor giants are brighter than the metal rich giants, and it is more likely to include distant metal poor halo giants because also of the r^2 factor. However, the trend seen in figure 7 is much too strong.

This result is difficult to understand. It means that either 1) there is a metal rich population of stars at intermediate distances and latitudes between us and the bulge (not likely), or 2) the distances for the metal rich stars suffer from some systematic effect, and are wrong (more likely). Going back to our assumptions for computing distances, we conclude that the distances for the metal rich giants might be too short because too old of an age was adopted. If the stars are younger, about 10 Gyr instead of 13–15 Gyr, the isochrones would be ~ 0.3 magnitudes brighter. The derived distances would then be 1 kpc larger at 7 kpc, and 0.5 kpc larger at 3 kpc. This will bring the distance distribution along the line of sight into a better agreement with the expectations from Appendix 1. This is another indication, albeit indirect, that the bulge giants are younger than typical halo giants. (The computed distance to M22 would not be very affected by this stretching of the scale which we apply only to the metal rich stars).

This effect illustrates very nicely the problems with measuring distances: aside from choosing R_0 and isochrones, one has to assume an age-metallicity relationship. We do not know the age of the bulge with certainty, much less its dependence on metal abundance. Therefore, one should prefer the observed values (V_{los} and σ_{los}) rather than the projected values (V_ϕ and σ_ϕ), which needed distances to be derived. For bulge fields, it is much better to assume that all the stars are at the same distance, rather than try to measure distances.

On the other hand, we expect to see a mild trend with metallicity because of the bright magnitude limit ($V \sim 15$) for this sample, we expect most of the metal rich giants to be on the near side of the bulge. We assumed a power law luminosity function, and estimated the mean distance that the metal rich stars would have given a reddening of $E(B-V) = 0.32$ for the field. A reasonable choice of the luminosity function is that of Bahcall & Soneira (1980) presented in Appendix 1. For that luminosity function and the faint magnitude cutoff imposed, we find that the mean distance should be $0.94 R_0$, or 7.52 kpc for $R_0 = 8$ kpc. Still, this is not enough (a difference of only 0.13 magnitudes) to account for the effect seen in figure 7. This estimate of the mean distance does not change if we use the bulge luminosity function of Terndrup & Blanco (1988).

In summary, to bring the mean distance of the metal rich stars into agreement with these models, an age of ~ 10 Gyr would be predicted by the Bergbusch & Vandenberg (1992) isochrones.

5.5. Kinematics *vs* Metallicity

We will study the dependence of the kinematics on the metal abundances in this field, as we did in the field F588. Hereafter, all the dispersions quoted have been corrected for the intrinsic error. The velocities listed in table 1 are Heliocentric. From now on, we will refer to the Galactocentric system, correcting the heliocentric velocities for the motion with respect to the local standard of rest according to Delhaye (1965), and correcting for the Solar orbit around the Galaxy by the additive factor $220 \sin(l) \cos(b)$ (Gunn, Knapp & Tremaine 1979). The kinematics of different groups considered in the following sections are summarized in table 3.

5.5.1. The M22 Members

The stars members of M22 according to proper motions and radial velocities are identified in table 1. We have observed 3 horizontal branch stars in M22. These give inaccurate radial velocities, because adequate templates are not available. That is the reason why the M22 velocity dispersion listed in table 3 is so high. Neglecting the HB stars, the M22 velocity dispersion becomes $\sigma_{M22} = 24/pm6$, in agreement with our earlier estimates of the velocity errors. We recall that M22 has an intrinsic velocity dispersion of $\sigma_0 = 8 \text{ km s}^{-1}$ (Pryor & Meylan 1993).

Table 5.3: KINEMATICS VS METALLICITY IN THE M22 FIELD

[Fe/H]	N	mean	err	stddev	err	V+50/sig
[-2.0 to -1.5]	9	-97.8	36.9	110.0	26.1	-0.43
[-1.5 to -1.0]	17	-42.2	19.7	81.1	13.9	0.10
[-1.0 to -0.5]	20	-13.5	11.8	53.1	8.4	0.69
[-0.5 to 0.0]	18	16.6	17.0	72.4	12.1	0.92
[0.0 to +0.5]	14	5.8	13.4	50.3	9.5	1.12
[bright V<14.]	7	-20.3	22.7	59.9	16.0	0.50
[M stars]	11	2.6	17.6	58.4	12.4	0.90
[M22 giants]	12	-159.1	14.3	49.5	10.1	
[Fe/H < -1.0]	26	-64.5	18.1	92.6	12.8	-0.16
[Fe/H > -1.0]	63	2.2	7.9	59.4	5.3	0.89

5.5.2. The Bright Stars

The sample is divided into stars brighter and fainter than $V = 14.0$. Taken as a whole, the brighter giants have halo-thick disk kinematics, with $\langle V_r \rangle = -31 \pm 24 \text{ km s}^{-1}$, and $\sigma = 80 \pm 17 \text{ km s}^{-1}$. However, 4 of the 11 stars brighter than $V = 14$ have $[\text{Fe}/\text{H}] \leq -1.0$. These should be included in the halo sample, discussed in the next paragraph. The rest 7 stars have very small velocity dispersion and mean velocity near zero: $\sigma = 60 \pm 16$, and $\langle V \rangle = -20 \pm 23 \text{ km s}^{-1}$. These are consistent with disk kinematics.

5.5.3. The K giants

There are 74 K giants fainter than $V = 14$ in our sample. We will include the 4 brighter metal poor stars in this sample. These are divided according to metal abundance. The 52 bulge K giants with $[\text{Fe}/\text{H}] \geq -1.0$ have $\langle V \rangle = 9 \pm 10$, and $\sigma = 70 \pm 7$. The 26 stars more metal poor than $[\text{Fe}/\text{H}] = -1.0$ have $\langle V \rangle = -64.5 \pm 17.8$, and $\sigma = 90.6 \pm 12.6 \text{ km s}^{-1}$. These two groups have different kinematics, the mean velocities differ by $3.6 \sigma_V$, and the velocity dispersions differ by $1.5 \sigma_\sigma$ (these σ_V and σ_σ are the combined errors). These are indeed two different populations. We identify the giants with $[\text{Fe}/\text{H}] \leq -1.0$ as being primarily halo stars, and the others as bulge giants. These results are consistent with the findings of chapter 4 in the field F588.

Figure 8 shows the radial velocities vs metal abundances for bulge and M22 giants. This figure shows a clear trend, the more metal rich stars seem to have higher mean velocity and lower velocity dispersions than the metal poor ones.

Figure 5.8 Heliocentric radial velocity *vs* final metallicity for stars with $V \leq 14$. The M22 giants are shown with filled circles.

We bin the K giant data according to metallicity, excluding the M22 giants, to compute the mean Galactocentric velocities and velocity dispersions. Table 3 presents the results for the 5 bins having about 10–20 stars each. Figures 9 a to c show the dependence of kinematics on metallicity. The most metal poor bin, with highest velocity dispersion and lowest rotation, can be taken as pure halo, with zero contamination from the other Galactic components. The next bin, including stars with $-1.5 \leq [Fe/H] \leq -1.0$ still shows halo kinematics, but there is a hint of the transition to the colder bulge kinematics shown by the rest of the giants with $[Fe/H] \geq -1.0$. Even though the effects are not as marked as seen with the more extensive dataset of field F588, the trends are clear, and consistent with the results of chapter 4.

The relative number of halo stars in this field is large compared with the number of bulge stars. This is due to the relatively bright magnitude limit in V of the C86 sample. Very metal rich stars (with $[Fe/H] \geq -0.3$) at the distance of the bulge (8 kpc) would not be included in the present sample. The metal rich bulge stars included have to be much closer than that. For example, a star near the tip of the metal rich globular cluster NGC 6553 with $[Fe/H] = -0.2$ (Ortolani et al. 1992) has $M_V = -2$. Such star placed at 8 kpc and reddened by $E(B-V) = 0.32$ would have an apparent visual magnitude of $V = 15.5$, just fainter than the magnitude cutoff of the present sample.

Therefore, one should assume that this sample is mostly representative of the metal poor part of the bulge population, and biased towards distances smaller than R_0 .

Figure 5.9 a) Mean Galactocentric radial velocity *vs* metallicity for giants in the field of M22. Cluster giants are not included, neither are giants brighter than $V = 14$. Each of the bins has ~ 30 stars. b) Measured line of sight velocity dispersion *vs* metallicity. c) Degree of rotational support *vs* metallicity.

Still, the sample of bulge giants with $[\text{Fe}/\text{H}] \geq -1.0$ studied here is large enough to see that there is a trend between kinematics and metal abundance, like that found in field F588. The 3 metal rich bins of figure 9 attest to that. The more metal rich bulge giants appear to be more rotationally supported than the metal poor bulge K giants (figure 9 c). The dissipational collapse of bulge formation will have such a signature.

5.5.4. The M Giants

The M giants in this field have intermediate kinematics. They are not very numerous, but it is clear that they follow bulge kinematics rather than the halo or the Galactic disk. The 11 M giants in this field have $\langle V_G \rangle = 3 \pm 18$, $\sigma_r = 58 \pm 12$, and. $\langle V_G \rangle / \sigma_r = 0.90$. These values correspond to the kinematics of the K giants with $[\text{Fe}/\text{H}] \sim 0.0$, as seen in figures 9 a, b and c.

5.6. Conclusions

We have discussed how valuable (however difficult) the measurements of proper motions in low latitude clusters a la C86 are. More such work will give enormous insights for Galactic studies.

We have discriminated bulge giants from giants belonging to the cluster, confirming in some cases where the proper motions give intermediate membership probabilities.

We have tried to measure distances, and found that the metal rich giants are much closer in the mean than the bulge. We argue that this is because

the bulge giants with $[\text{Fe}/\text{H}] \leq -1.0$ are significantly younger than the 13–15 Gyr isochrones used to derive distances. This agrees with the recent results of Holtzman et al. (1993). However, the sample is not complete, due to the bright limit cutoff of the C86 data, so we cannot determine the mean age of the bulge by this procedure. With a complete sample, we know that the distribution of the metal rich giants should peak at the distance R_0 , and we would be able to determine the mean age of the bulge with respect to the halo. This has not been tried before because people did not associate the metal poor giants in bulge fields with the halo.

The velocity dispersion decreases for the metal rich subsample of bulge giants. Similarly, the degree of rotational support increases with metallicity, resembling the behavior of the larger sample studied in the field F588.

6. KINEMATICS OF A LOW LATITUDE FIELD

We have obtained spectra for more than 300 stars in the low latitude field at $l, b = (12, 3)$ degrees. We discuss the discrimination of the different Galactic components (disk, halo and bulge) that contribute in this field. The variable reddening is used to obtain pure disk samples. The metallicity is used to obtain pure halo samples. The kinematics of these components are studied in relation to other fields in the inner Galaxy. The specific results are: 1) In field F589 the halo has $\langle V \rangle = 22 \pm 24 \text{ km s}^{-1}$, and $\sigma = 107 \pm 17 \text{ km s}^{-1}$. In this field too, the bulge and halo seem to be two separate components. 2) The velocity dispersion of the halo does not change much with distance from the Galactic center. 3) The nearby disk in that direction has $\langle V \rangle = 74 \pm 13 \text{ km s}^{-1}$, and $\sigma = 64 \pm 9 \text{ km s}^{-1}$, as found from 26 giants brighter than the bulge AGB tip. 4) The giants fainter than $R = 13.3$ with $[\text{Fe}/\text{H}] \geq -1.0$ have $\langle V \rangle = 85 \pm 7 \text{ km s}^{-1}$, and $\sigma = 70 \pm 5 \text{ km s}^{-1}$. These are mostly bulge giants.

6.1. Introduction

One of the big problems of understanding the kinematics in the inner regions of the Galaxy is that different tracers belong to different Galactic components, and it is not always obvious which population one is observing. For example, we have argued before that the well known bulge RRLyrs at Baade's window belong to the halo. This chapter is a study of a lower latitude field, with emphasis on separating the bulge from the disk.

Unfortunately, the kinematics and chemical composition of the old disk in these directions are poorly known. Janes (1979) finds a steady increase in the mean metallicity with decreasing Galactocentric radius for open clusters with $R \leq R_0$, and argues that the rise levels off at $[\text{Fe}/\text{H}] \approx 0$ at about $R \sim 4$ kpc. These results are confirmed by Neese & Yoss (1988). Lewis & Freeman (1989) find that the velocity dispersion of the old disk increases towards the Galactic center, while the metal abundance does not vary with Galactocentric distance in the central region. It will be very difficult then to separate the disk from bulge giants in these fields. The only promising way to discriminate between them would seem to be through accurate distance and proper motion information, which might reveal more subtle differences in spatial or kinematical properties (Freeman 1987).

We have identified a low extinction window of ~ 30 arcmin radius centered at $\alpha = 17^{\text{h}}58^{\text{m}}$, $\delta = -17^{\circ}30'$. The study of field F589 is more complicated than that of field F588 due to the fact that it lies at a lower latitude, with much more disk contamination, and differential reddening. We will use our findings in field F588 as a reference here. Note that the location of this field with respect to F588 determines that the total number of bulge giants should be very similar in both fields, for a flattened bulge with $b/a \sim 0.7$. On the other hand, the total number of disk giants will be much higher in F589, because it has a lower latitude than F588.

This field was chosen because it is important to be able to separate kinematically the disk from the bulge and halo in the inner Galaxy. Different

tracers such as RRLyrs, planetary nebulae, Miras, OH/IR stars, give different results, and it would be nice to determine which stars of each type belong to each Galactic component. This will facilitate the modeling and interpretation of the kinematics and dynamics of the inner bulge, and its connection to the Galactic center. It is painfully obvious that this task cannot be accomplished in any other galaxy in great detail.

This chapter is organized as follows. In section 2 we present the field, discuss the reddening variations, and give the selection of giants for the spectroscopy. Section 3 describes the photometry and selection of giants. Section 4 presents the spectroscopic data and their reductions. Section 5 discusses the radial velocity determinations. Section 6 gives the metallicity determinations. Section 7 evaluates the pros and cons of determining distances. Section 8 summarizes all the data (photometry, velocity and metallicity) for the observed sample. Section 9 discusses the contamination by disk giants. Section 10 discusses the contamination by disk dwarfs. Section 11 discusses the contamination by the thick disk. Section 12 discusses the halo kinematics. Section 13 discusses the disk kinematics. Section 14 discusses the bulge kinematics. Section 15 discusses the kinematics of the M giants. Finally, section 16 summarizes the conclusions.

6.2. The Field F589

M. Irwin scanned for us a region of 1.5×1.5 degrees centered in these coordinates with the APM machine in Cambridge. The extension of the scanned field implies that a very obscured region to the SE of the window is included.

The division between the window and the obscured region is very clear in the Palomar and ESO survey plates. Figure 1 a reproduces the Palomar plate field of 1.5×1.5 degrees scanned with the APM. Figure 1 b shows a map of the same region, where we have plotted all the stars with $R \leq 12.3$ measured by APM. We divide the field in 3 regions, 0, 1, and 2, according to increasing obscuration. Region 0 is the clear window, centered in figure 1 a and b. Region 2 is the very reddened part of the field, located to the SE of the field. We are going to take advantage of the location of this field, along with the reddening inhomogeneity, to study at the same time the bulge and the disk kinematics. A large sample is needed to decouple these 2 components, but we know at least that disk stars alone are present in the obscured region.

The field is extended in Galactic longitude, from $l = 10.7$ to 12.5 degrees. There is a well known gradient in the bulge kinematics vs Galactocentric distance (Minniti et al. 1992), however, we will take the field as uniform in kinematics, since the differences from one extreme to the other are not going to be significant. Likewise, the field extends in Galactic latitude from $b = 1.7$ to 3.2 , implying different contributions from the old disk. However, the reddening effects are much more important, and we will assume all the observed stars are located at the center of the field, at $l, b = (11.9, 2.7)$.

We assume the extinction law given in the model presented in Appendix A. Figure A1 shows that most of the extinction in the F589 window is expected to occur within 2 kpc of the Sun. In the reddened part of the field (with a mean latitude $b \sim 2^\circ$), contribution from more distant clouds is expected up

Figure 6.1 a) Map of the field, reproduced (contrast enhanced) from the Palomar Observatory Sky Survey J plate E-1106 (National Geographic Society). The field shown is 1.5×1.5 degrees centered at $\alpha = 18^h 00^m$, $\delta = -17^\circ 30'$. North is up and East to the right. The non-uniform reddening across the field is clearly seen. The clear window is seen in the central $\sim 30 \times 30$ arcminutes of the field. The SE part is more obscured by ~ 1 magnitude.

Figure 6.1 b) Map of the APM stars with $R \geq 12.3$ in the same scale as (a). Different stellar density corresponds to different reddening. Regions 0, 1, and 2 are marked (see text for explanation).

to ~ 4 kpc. In the clear part of field F589 (the F589 window), distant disk, halo and bulge giants are expected to have the same uniform extinction within the window. The total amount of extinction is scaled to match the observed reddening in this field. The reddening in the field is variable, but we divide the field into 3 regions and assume it remains approximately constant within a single region. Clearly this procedure is an oversimplification, but it would be enough for our purposes.

6.3. The Photometry

The photographic material comes from scans of BRI plates done at the APM machine by M. Irwin (described in chapter 4). These data provided accurate coordinates for the positioning of the fibers, as well as magnitudes and colors suitable for the selection of giants in the field. We have obtained BRI CCD frames to calibrate the APM photometry. Unfortunately, there are very few stars in common between the CCD frames and the APM. We note that the only stars kept by the APM are these that are isolated, in the three filters. This is a very restrictive criterion in very crowded fields such as F589, where the stellar density is 1.7 times that of F588 (in the less reddened regions). As a consequence, the photographic APM photometry was calibrated with respect to the F588 field. This is not expected to cause any problems, since we have found the transformations between CCD and APM magnitudes to be linear. Therefore, the errors involved in the photometry are the same as discussed previously for the field F588. Note that in this field the major concern with the photometry

is the reddening variations, rather than the intrinsic or calibration photometric errors.

Figure 2 shows color-color and color-magnitude diagrams (CMDs) for the very reddened part of F589 (top panel) and for the F589 window (bottom panel).

The selection of candidate for the spectroscopy is the same as that applied to the field F588, based on the color-color and color-magnitude diagrams produced by the APM machine. First, a faint limit was imposed for the photographic R magnitudes at $R \approx 12.3$, then all the reddest stars in both B_J - R and R - I colors were selected. The limits in colors were chosen to correspond to the locus of K stars, as judged by comparison with a typical APM color-color diagram of a high Galactic latitude field. The selection of the sample is also chosen to avoid including large numbers of M giants, for which the determination of temperatures and abundances is more problematic. However, the occasional M giants observed are used as a check for the kinematics of the metal rich K giants.

The samples are roughly divided into bright and faint. The bright sample was observed at the MMT with Red Channel and at the 90" with MX. The faint sample comes from Du Pont telescope at Las Campanas Observatory (LCO). For the LCO run we selected the faintest stars possible to observe, so that we can avoid being biased to low metallicity giants, which are always brighter. This is very important, because we see in the brighter MX and MMT samples that the fraction of metal poor giants is high. The color-color diagrams and CMDs of the giants for which we have spectra are shown in figure 3.

Figure 6.2 APM and CCD color-color diagrams and color-magnitude diagrams for F589. The top panels shows the reddened region 2 of the field. The bottom panels show the F589 window (region 0).

Figure 6.3 Optical color-magnitude diagrams and color-color diagram of the stars with spectra in the field F589. The MX and Red Channel observations are plotted as crosses. The observations from Las Campanas are the squares.

6.4. The Spectroscopy

6.4.1. The Observations

The observations with the multiobject spectrograph MX at the Steward Observatory 90" telescope and with the Red Channel Spectrograph at the MMT are described by Minniti et al. (1992), and in chapter 3. A few stars observed at the MMT run do not have photometry. These are field stars that fall on the slit, and have K giant spectra.

The observations at the 100" Du Pont telescope at LCO were obtained by A. McWilliam and M. Rich in the nights 19 and 20 June 1992. These were bright nights, and some cirrus were present at times. The instrument was the Multi-Object Fiber Spectrograph, that uses a 2D-Frutti photon counting system (Schectman 1978, 1984). It consists of 128 plug-in fibers that feed the Bowen-Schmidt camera. A description of the instrument is given by Schectman (1993). The 600 line grating blazed at 5000 Å was used in 1st order.

The observations were taken at 1.0–1.4 airmasses. The order of exposures was first a HeNeAr comparison lamp, then the object setup, and then the sky. For the bright standards no sky exposure was taken. Even though there are fibers dedicated to the sky in each setup, it was judged that these were not going to be enough for subtracting the high background, and independent sky exposures were taken. The sky subtraction then can be made on a fiber-to-fiber basis. About 8–10 fibers were not used for different reasons. All along the run the background counts were high due to moonlight. Thin cirrus also interrupted

the observations one time. The exposure times ranged between 400 and 5700 sec for the individual setups. The radial velocity standards were imaged in only one fiber. The spectral resolution was measured from the FWHM of the lamps and sky emission lines to be 370 km s^{-1} . The spectra were trimmed to a final spectral coverage from 3900 to 7000 Å. These includes several strong spectral features for the cross correlations, and avoids shorter wavelengths where the Solar spectrum dominates.

6.4.2. The Reductions

The reductions of the 90" and MMT datasets are also described by Minniti et al. (1992) and in chapter 3. Here we will concentrate on a brief summary of the reductions of the LCO data.

We used the IRAF routines within the CCDRED package to reduce the frames. Every step of the reduction was done interactively. First the background is subtracted using the unexposed parts of the frame. The frames were then trimmed to leave only the regions of interest. Then they were divided by a high S/N flat-field (dome quartz lamp) that was previously fit by a high order surface, to remove the pixel to pixel response of the detector.

We used the IRAF routines within the ARGUS and HYDRA packages to extract the spectra. During the reduction procedure, we have only extracted 120 spectra per setup.

6.5. The Velocities

The spectra were binned into 2048 channels for the cross correlations. Each channel has the equivalent to 82 km/s. The errors in the velocities are about 2 times the error in the Argus velocities. Typically, in a single setup with 120 fibers, about 80 good velocities are obtained. The rest of the spectra are of lower S/N, and the velocities measured with respect to 3 different templates do not agree as well. The templates are 3 late type stars, we did not use the sky spectrum itself because it would result in a spurious peak at zero velocity for the spectra where the sky is not completely accounted for.

The velocities with respect to the 3 different templates agree with each other for the higher S/N spectra, with one of them giving slightly different velocities. This has been given a lower weight. The rms of the velocities correlated with the 3 templates is typically ≤ 24 km/s for the spectra with good S/N. The individual radial velocities are then good to ≤ 24 km/s for a single setup with different exposures, and good to ≤ 30 km/s in general. For the whole sample, the average velocity errors from cross-correlation with the different templates is 30 km/s, with most of them between 13 and 35 km/s. The velocities with rms errors larger than 40 km/s were discarded. These were all low S/N spectra, we will analyze the high quality data here, leaving the rest for the future. If we treat the velocities differently (i.e. considering all velocities but weighting them by the respective errors), have little effect on the conclusions. Hereafter, all the computed velocity dispersions will be accounted for the intrinsic errors.

Unfortunately, there are no standards in common between the LCO and the other runs. Thus, to set the zero point we have relied on the twilight sky spectrum. This agrees with the zero point defined by the radial velocity standards by 15 km/s.

An independent estimate of the errors is given by 3 different exposures with the same setup. These were obtained because a single exposure had low counts due to clouds and high moonlight. For the final velocities we have added up all the spectra for each single star, and run the cross correlations in the high S/N spectra (these are the velocities listed in table 2). However, we have also run the cross correlations on each of the 3 different exposures, to estimate the errors. There is no systematic shift between these 3 different exposures. One of them has very low S/N spectra. For about 80 good S/N spectra in the 3 exposures, the rms is 24 km/s.

Another estimate of the errors is given by cross correlating all the sky spectra. They will result in an optimistic error, since they have in general good S/N, and emission lines. The rms error for 120 fibers is 22 km/s, with the largest deviation being 82 km/s from the mean.

In summary, the individual radial velocities for the LCO run are good to 28 km/s rms. The zero point is good to 10 km/s. We have chosen not to consider about 35% of the sample with lower S/N; only the higher quality velocities are reported here. The individual radial velocities for the MX and MMT runs are good to 8 and 6 km/s, respectively, with a zero point error of 10 km/s.

6.6. The Metal Abundances

In chapter 3 have calibrated the strength of the Mg 5175Å + Fe 5270Å + Fe 5335Å vs color for a large number of globular and open clusters and field giants. We will use the same grid and definition of indices. Note that the LCO spectra have a much broader spectral coverage, including several other features that are potentially good metallicity indicators. However, we will use only the indices measured for the other data sets, to be consistent. This will also allow a direct comparison with the other fields.

The indices measured for the MX and Red Channel runs are more accurate than the LCO, due to the lower resolution and S/N of the latter sample. We have measured all of the Fe line indices for the data from Las Campanas, even though the weaker Fe features (Fe5920, Fe5980, Fe5011) are not sensitive to metallicity due to the lower resolution. These lines were found to be marginally sensitive to metallicity in the MMT , Argus and Mx data, but were not used to measure $[\text{Fe}/\text{H}]$.

Unfortunately, there are no stars in common between the LCO run and the other observing runs used to set up the calibration. Therefore, there is no direct way to make the transformations between the different runs other than the twilight sky. However, we can use the mean values of the indices measured in the MX and Red Channel runs to find the zero point for LCO indices. This has been done using only the stars with similar colors and magnitudes, to avoid the confusion of measuring different stellar populations. The mean offsets are small, as expected, but significant. These zero point offsets are not surprising

giving the different telescopes, instruments, and resolutions of the different data.

We found

$$\Delta Mg = 0.10, \Delta Fe5270 = -0.08, \Delta Fe5335 = 0.09, \Delta H\beta = 0.02$$

The other indices will not be discussed here, as we found in chapter 3 that they are not very useful in comparison.

The zero point shifts determined from the Solar spectrum (twilight sky) are in the sense Argus – LCO:

$$\Delta Mg = 0.08, \Delta Fe5270 = 0.03, \Delta Fe5335 = 0.11, \Delta H\beta = 0.04$$

These are in good agreement with the zero point shifts determined from the stars with similar colors and magnitudes. This is reassuring evidence that the zero point shifts are not just due to different stellar populations observed.

The twilight sky is also useful to determine the errors in the indices. For 120 fibers with the Solar spectrum, we find $\sigma Mg = 0.05$, with a total range from 0.79 to 0.91, $\sigma Fe5470 = 0.05$, with a total range from 0.81 to 0.96, $\sigma Fe5335 = 0.06$, with a total range from 0.58 to 0.86, $\sigma Mg2 = 0.04$, with a total range from 0.65 to 0.81, and $\sigma MgH = 0.06$, with a total range from 0.78 to 1.02. We note that these are optimistic errors, since the sky spectra were well exposed. The true errors for the bulge giants would be slightly higher. We estimate that the final metallicities derived from the LCO data will have larger errors than the Argus data, $\sigma[Fe/H]_{LCO} \sim 1.5\sigma[Fe/H]_{Argus}$, due mostly to the lower resolution. This estimate is based on the scatter of the sky indices, on the multiple exposures,

on the total scatter of the giants in the F589 window compared with the F588 window, and taking into account the larger reddening variations in field F589.

Note that since a large number of disk giants are included in our sample, their metallicities derived with the present calibration may be wrong. As discussed in Chapter 2, the calibration of the indices was done neglecting field disk giants and open cluster giants, using only globular cluster giants. The argument was that whatever the chemical evolution history of the bulge, we assume that it is similar to the metal rich globulars. This may not be true for disk giants, which have a different chemical evolution. Different ages and element to Iron ratios for disk giants determine that the globular cluster calibration is not applicable (e.g. compare Wheeler et al. 1990 with Edvarsson et al. 1993).

Since we cannot pinpoint which stars are disk and which bulge giants, however, we determine metallicities for all the giants using our calibration. These $[\text{Fe}/\text{H}]$ values are not correct for disk giants, but they still allow the ranking between samples of different line strength at the same color, which is related to $[\text{Fe}/\text{H}]$. Thus, relative comparison between stars of different line strengths is still possible.

6.7. What About Distances?

For field F589, the FWHM of the line of sight depth for a $r^{-3.5}$ density law is only 0.7 magnitudes in this field. Thus, the errors involved assuming that all the stars are at the same distance would be then of the order of 30%. This error is of the same order as the error achieved with spectroscopic parallax methods,

with the great advantage that there are no systematics involved (other than the distance to the Galactic center, known to only 10%).

6.8. The Data

In this section we summarize the whole data set, and give some figures illustrating the trends, before analyzing in detail the contribution from the different Galactic components in the field. Tables 1 and 2 present the final data sample. Table 1 gives the star ID and the 12 spectroscopic indices measured. Table 2 gives the photometry, velocities and metallicities. Columns 3 to 4 list the BRI photometry (mostly from the APM). Column 5 gives the radial velocities. The velocities with larger errors ($\sigma \geq 30 \text{ km s}^{-1}$) are flagged with an asterisk. Column 6 is the flag that identifies the different reddening zones. This flag is set to 0, 1 or 2 if the star is located in the in the clear window, in the field with intermediate obscuration, or in the very reddened field, respectively. Finally, column 7 presents the combined metallicity index $\text{Mg}+2\text{Fe}$.

Figure 4 plots the radial velocities *vs* R magnitude for the stars observed in the different reddening zones. This figure shows no particular structure, aside from that the stars in the most reddened region have smaller velocity dispersion.

Figure 5 shows the $\text{Fe5270}+\text{Fe5335}$ *vs* Magnesium indices for the giants in the F589 window, where the solid symbols represent the stars in the most reddened region 2. A comparison with the same figures for F588 and M22 fields reveals that the rest of the stars (open symbols) occupy the same region as bulge giants.

Table 6.1: SPECTRAL INDICES

Star	Mg	H β	Fe492	Fe498	Fe50	Fe53	Fe54	Mg1	Mg2	Mgb	MgH
1003	0.85	0.88	0.71	0.83	0.69	0.82	0.81	0.83	0.92	0.80	0.97
1005	0.80	0.80	0.73	0.77	0.80	0.91	0.87	0.71	0.81	0.69	0.91
1006	0.92	0.99	0.76	0.93	0.71	0.89	0.74	0.78	1.00	0.80	1.00
1007	0.89	0.83	0.83	0.87	0.75	1.05	0.80	0.88	0.98	0.86	0.98
1008	0.95	0.85	0.80	1.00	0.71	0.90	0.68	0.76	1.04	0.79	1.01
1009	0.98	0.81	0.76	0.90	0.94	0.91	1.05	0.87	0.98	0.68	0.98
1011	0.96	0.74	0.77	0.93	0.80	0.91	0.85	0.87	0.99	0.89	1.00
1012	0.94	0.84	0.77	0.91	0.73	0.91	0.77	0.79	0.99	0.88	0.86
1013	1.00	0.84	0.85	0.96	0.76	0.97	0.82	0.84	1.04	0.89	0.98
1014	0.93	0.82	0.84	0.95	0.76	0.89	0.77	0.83	0.95	0.88	0.91
1015	0.89	0.81	0.82	0.88	0.70	0.88	0.76	0.80	0.97	0.82	0.94
1016	0.89	0.89	0.77	0.79	0.75	0.91	0.84	0.68	0.94	0.78	0.98
1017	0.81	0.82	0.75	0.88	0.75	0.87	0.80	0.76	0.82	0.77	0.87
1018	0.90	0.80	0.75	0.84	0.77	0.89	0.82	0.77	0.93	0.75	0.96
1019	0.91	0.86	0.81	0.97	0.72	0.91	0.72	0.80	0.98	0.82	0.93
101A	0.75	0.86	0.86	0.77	0.69	0.97	0.77	0.86	0.79	0.78	0.95
101B	0.77	1.05	0.73	0.75	0.77	0.87	0.80	0.79	0.79	0.70	0.84
101C	0.96	0.91	0.81	0.84	0.84	0.93	0.92	0.73	0.99	0.76	0.95
1021	0.87	0.87	0.83	0.91	0.69	0.87	0.68	0.79	0.93	0.86	0.93
1022	0.89	0.81	0.78	0.91	0.71	0.90	0.75	0.82	0.94	0.82	0.93
1023	0.88	0.87	0.81	0.87	0.77	0.95	0.83	0.80	0.91	0.79	0.89
1025	0.86	0.88	0.82	0.91	0.70	0.88	0.76	0.73	0.89	0.81	0.90
1026	0.80	0.83	0.74	0.78	0.70	0.90	0.74	0.82	0.83	0.74	0.85
1027	0.97	0.90	0.83	1.12	0.67	0.89	0.73	0.79	1.07	0.93	0.97
1028	1.02	0.85	0.74	1.06	0.76	0.92	0.76	0.81	1.12	0.91	1.03
1029	0.84	0.84	0.78	0.78	0.73	0.90	0.75	0.82	0.89	0.76	0.92
102A	0.82	0.92	0.77	0.76	0.76	0.88	0.75	0.76	0.85	0.71	0.89
102B	0.80	0.83	0.74	0.82	0.71	0.93	0.74	0.81	0.83	0.70	0.89
102C	0.78	1.01	0.75	0.81	0.76	0.85	0.77	0.76	0.82	0.72	0.87
1031	0.85	0.82	0.79	0.93	0.72	0.92	0.78	0.73	0.91	0.82	0.96
1032	0.85	0.80	0.74	0.85	0.81	0.97	0.83	0.73	0.89	0.79	0.91
1033	0.86	0.85	0.81	0.83	0.79	0.94	0.85	0.72	0.89	0.75	0.94
1034	0.74	1.05	0.73	0.77	0.72	0.84	0.73	0.74	0.75	0.70	0.83
1035	0.84	0.85	0.81	0.77	0.73	0.89	0.77	0.75	0.88	0.76	0.89
1036	0.89	0.82	0.82	0.93	0.72	0.98	0.74	0.79	0.93	0.75	0.95
1038	0.74	1.01	0.72	0.77	0.73	0.84	0.77	0.77	0.78	0.68	0.88
1039	1.00	0.87	0.82	0.93	0.88	1.00	0.87	0.85	1.02	0.81	1.14
103A	0.82	0.86	0.74	0.70	0.81	0.91	0.90	0.75	0.84	0.71	0.93
103C	0.89	0.87	0.85	0.88	0.86	0.83	0.88	0.79	0.96	0.72	1.06
1043	0.80	0.81	0.83	0.84	0.78	0.75	0.80	0.55	0.85	0.68	0.84
1045	0.87	0.77	0.85	0.80	0.80	0.84	0.81	0.69	0.94	0.80	0.86
1047	0.86	0.64	0.74	0.88	0.88	0.78	0.80	0.64	0.89	0.76	0.75
1048	1.03	0.91	0.79	0.95	0.72	0.98	0.68	0.83	1.06	0.93	0.95
104A	1.01	0.82	0.78	0.98	0.73	0.89	0.77	0.73	1.11	0.80	0.97
104B	0.99	0.99	0.78	1.03	0.70	0.98	0.76	0.82	1.06	0.85	1.02
1053	0.94	0.79	0.78	0.97	0.68	0.91	0.71	0.76	1.08	0.88	1.05
1056	0.99	0.69	0.80	0.80	0.87	0.82	0.91	0.76	1.04	0.87	0.97
1057	0.97	0.84	0.92	1.20	0.52	0.92	0.55	0.86	1.20	0.79	1.17
1059	0.90	0.89	0.83	0.73	0.66	0.72	0.59	0.93	0.94	0.89	1.04
105A	0.79	0.67	0.78	0.80	0.70	0.85	0.70	0.75	0.86	0.81	0.79

Star	Mg	H β	Fe492	Fe498	Fe50	Fe53	Fe54	Mg1	Mg2	Mgb	MgH
105B	0.95	0.76	0.82	0.87	0.78	0.88	0.73	0.82	0.97	0.91	0.83
105C	1.04	0.85	0.95	1.22	0.76	0.86	0.90	0.77	1.11	0.84	0.96
105D	0.98	0.71	0.72	0.96	0.69	0.95	0.63	0.87	1.06	0.93	0.87
1061	0.96	0.82	0.81	0.98	0.77	0.88	0.74	0.75	1.03	0.87	0.88
1062	0.96	0.84	0.77	0.82	0.73	0.74	0.78	0.81	1.02	0.85	1.03
1063	0.95	0.72	0.83	0.90	0.77	0.83	0.74	0.73	0.95	0.90	0.82
1064	0.91	0.92	0.88	0.77	0.78	0.81	0.85	0.90	0.97	0.81	0.89
1065	0.98	0.86	1.18	0.87	0.83	0.77	0.78	0.75	1.02	0.86	0.90
1067	0.90	0.84	0.84	0.73	0.80	0.85	0.73	0.77	0.95	0.83	0.91
1068	0.87	0.73	0.80	0.84	0.76	0.84	0.72	0.70	0.92	0.76	0.83
1069	0.98	0.80	0.77	1.05	0.72	0.89	0.74	0.85	1.03	0.90	0.83
106A	0.95	0.72	0.78	1.04	0.73	0.78	0.70	0.74	1.06	0.84	0.93
106B	0.90	0.84	0.83	1.03	0.83	0.78	0.85	0.80	0.96	0.73	0.88
106C	1.07	0.84	0.79	1.08	0.69	0.85	0.70	0.80	1.16	0.96	0.94
106D	1.03	0.81	0.82	1.03	0.73	0.90	0.73	0.73	1.09	0.89	0.96
1071	0.88	0.83	0.95	0.77	0.69	0.87	0.75	0.76	0.92	0.76	0.84
1072	0.99	0.78	0.76	0.96	0.65	0.85	0.58	0.75	1.12	1.03	0.96
1073	0.94	0.70	0.96	0.74	0.85	0.84	0.94	0.82	0.92	0.78	0.84
1074	0.93	0.73	0.76	0.89	0.79	0.75	0.79	0.77	0.99	0.83	0.83
1075	0.96	0.85	0.79	0.99	0.80	0.81	0.77	0.78	1.00	0.83	0.89
1078	1.08	0.84	0.83	1.03	0.77	0.97	0.77	0.77	1.15	0.96	0.98
1079	0.99	0.86	0.78	0.91	0.70	0.88	0.71	0.74	1.06	0.88	1.02
107A	1.09	0.82	0.83	1.06	0.75	0.95	0.81	0.83	1.12	0.99	1.02
107C	1.00	0.83	0.77	1.05	0.77	0.94	0.82	0.83	1.00	0.83	0.83
107D	0.97	0.88	0.75	1.14	0.63	0.89	0.67	0.74	1.08	0.90	0.91
2001	0.82	0.82	0.79	0.76	0.76	0.91	0.77	0.87	0.92	0.74	1.03
2002	0.87	0.92	0.81	0.85	0.80	0.85	0.87	0.74	0.92	0.74	0.87
2003	0.88	0.90	0.75	0.95	0.74	0.95	0.84	0.72	0.99	0.74	0.93
2004	0.82	0.75	0.81	0.91	0.72	0.75	0.84	0.63	0.90	0.67	0.80
2006	0.93	0.92	0.79	0.97	0.78	0.85	0.80	0.72	1.01	0.77	0.93
2007	0.73	0.71	0.83	0.86	0.67	0.90	0.71	0.76	0.79	0.76	0.83
2008	0.86	0.81	0.81	0.87	0.79	0.84	0.77	0.82	0.95	0.64	0.95
200A	0.90	1.05	0.78	0.85	0.76	0.91	0.76	0.92	1.03	0.68	0.98
200B	0.86	0.86	0.77	0.88	0.74	0.85	0.73	0.80	0.88	0.69	0.76
200C	0.95	0.89	0.83	0.89	0.79	0.86	0.75	0.89	1.03	0.75	0.93
2011	0.96	0.79	0.79	0.94	0.73	0.92	0.75	0.77	0.97	0.86	0.90
2012	0.92	0.77	0.78	1.03	0.63	0.85	0.67	0.78	1.05	0.80	0.95
2013	0.99	0.88	0.83	0.99	0.70	0.87	0.78	0.80	1.14	0.87	1.04
2014	0.98	0.77	0.85	1.05	0.75	0.90	0.74	0.79	1.04	0.85	0.91
2015	0.95	0.69	0.82	1.21	0.71	0.94	0.74	0.85	1.04	0.92	0.89
2016	0.93	0.87	0.80	0.86	0.78	0.86	0.82	0.74	0.96	0.81	0.91
2017	0.85	0.82	0.77	0.85	0.75	0.85	0.78	0.75	0.91	0.76	0.95
2018	0.98	0.79	0.78	0.94	0.76	0.92	0.80	0.77	1.04	0.81	0.96
2019	0.90	0.84	0.81	0.98	0.71	0.90	0.75	0.75	0.99	0.79	0.91
2066	0.93	0.68	0.91	0.93	0.77	0.81	0.75	0.79	0.96	0.84	0.81
201B	0.85	0.87	0.73	0.97	0.76	0.81	0.77	0.76	0.95	0.70	0.92
201C	0.85	1.00	0.85	0.84	0.86	0.94	0.89	0.64	0.89	0.65	0.93
2021	0.82	0.89	0.81	0.80	0.73	0.85	0.76	0.70	0.85	0.74	0.87
2022	0.86	0.79	0.77	0.85	0.74	0.92	0.77	0.74	0.90	0.76	0.93
2023	1.02	0.92	0.78	1.14	0.70	0.94	0.71	0.80	1.06	0.90	0.90
2024	0.91	0.94	0.74	0.90	0.80	0.87	0.92	0.81	0.92	0.71	0.92

Star	Mg	H β	Fe492	Fe498	Fe50	Fe53	Fe54	Mg1	Mg2	Mgb	MgH
2025	1.01	0.86	0.80	1.04	0.71	0.83	0.74	0.87	1.05	0.89	0.92
2026	0.98	0.87	0.81	1.18	0.64	0.99	0.70	0.83	1.11	0.89	0.95
2027	0.94	0.86	0.75	0.92	0.76	0.88	0.81	0.82	0.98	0.80	0.98
2028	0.92	0.80	0.79	1.03	0.66	0.88	0.69	0.77	1.04	0.82	1.01
2029	0.85	0.86	0.78	0.80	0.74	0.87	0.78	0.80	0.91	0.75	0.93
202A	0.85	0.87	0.83	0.86	0.74	0.90	0.75	0.72	0.91	0.74	0.94
202B	1.01	0.75	0.74	1.10	0.66	0.90	0.66	0.79	1.11	0.89	0.92
202C	0.87	0.79	0.83	0.90	0.74	0.88	0.80	0.73	0.94	0.78	0.90
2031	0.91	0.82	0.75	0.94	0.75	0.97	0.81	0.84	0.98	0.80	0.92
2032	0.89	0.83	0.70	0.91	0.75	0.91	0.81	0.70	0.98	0.78	0.99
2033	0.93	0.85	0.78	0.99	0.73	0.94	0.78	0.79	0.98	0.80	0.90
2034	0.79	0.88	0.76	0.84	0.71	0.87	0.74	0.79	0.84	0.75	0.86
2035	0.97	0.84	0.74	1.19	0.65	0.91	0.67	0.79	1.08	0.90	0.87
2036	0.81	0.81	0.74	0.83	0.72	0.87	0.78	0.75	0.84	0.71	0.87
2037	0.78	0.99	0.75	0.90	0.72	0.88	0.77	0.72	0.82	0.71	0.81
2039	0.89	0.72	0.74	0.86	0.72	0.91	0.62	0.84	1.08	0.74	0.89
203A	0.84	0.87	0.75	0.86	0.80	0.90	0.85	0.70	0.90	0.71	0.91
203C	0.82	0.91	0.79	0.83	0.76	0.86	0.85	0.76	0.89	0.76	0.93
2042	0.88	0.65	0.83	0.85	0.75	0.75	0.83	0.87	0.95	0.74	0.80
2043	0.79	0.78	0.75	0.84	0.72	0.88	0.79	0.96	0.90	0.66	0.93
2044	0.79	0.87	0.86	0.94	0.71	0.85	0.70	0.57	0.91	0.72	0.85
2045	0.92	0.84	0.83	0.98	0.87	0.81	0.88	0.72	0.95	0.78	0.74
2046	0.83	0.84	0.85	0.84	0.77	0.78	0.76	0.74	0.89	0.73	0.87
2047	0.92	0.74	0.81	0.96	0.79	0.79	0.73	0.76	0.96	0.81	0.70
2048	0.98	0.85	0.80	0.97	0.78	0.90	0.80	0.83	1.02	0.82	0.91
2049	0.91	0.83	0.79	1.08	0.69	0.87	0.72	0.79	1.01	0.78	0.91
204A	0.90	0.84	0.81	0.93	0.77	0.86	0.81	0.77	0.97	0.78	0.96
204B	0.89	0.80	0.81	0.94	0.72	0.94	0.77	0.81	0.97	0.79	0.92
204C	0.92	0.87	0.81	0.85	0.74	0.91	0.77	0.81	0.97	0.76	0.93
204D	0.95	0.95	0.83	0.97	0.78	0.86	0.81	0.64	1.03	0.74	0.91
2051	0.95	0.81	0.80	1.00	0.69	0.90	0.72	0.78	1.05	0.84	0.98
2052	0.84	0.97	0.81	0.91	0.74	0.95	0.81	0.90	0.95	0.78	0.96
2053	0.88	0.73	0.77	0.91	0.78	0.87	0.79	0.79	0.96	0.79	0.98
2054	0.76	0.78	0.74	0.75	0.73	0.75	0.68	0.76	0.84	0.67	0.89
2055	0.93	0.95	0.73	0.98	0.73	0.90	0.76	0.74	1.00	0.79	0.75
2057	0.94	0.82	0.86	0.83	0.77	0.90	0.86	0.91	1.04	0.75	1.03
2058	0.79	0.76	0.78	0.82	0.76	0.81	0.79	0.77	0.81	0.74	0.80
2059	0.90	0.80	0.84	0.85	0.78	0.85	0.69	0.83	0.92	0.81	0.84
205A	0.83	0.76	0.80	0.81	0.69	0.82	0.62	0.76	0.95	0.80	0.87
205B	0.85	0.76	0.73	0.90	0.73	0.85	0.66	0.74	0.91	0.85	0.80
205C	0.96	0.78	0.94	1.01	0.83	0.83	0.93	0.68	0.99	0.69	0.86
205D	0.95	0.78	0.75	0.85	0.75	0.81	0.73	0.80	0.98	0.84	0.81
2061	0.95	0.78	0.79	1.00	0.73	0.86	0.75	0.79	1.05	0.83	0.91
2062	0.92	0.88	0.83	0.93	0.77	0.73	0.90	0.88	0.97	0.77	0.92
2063	1.00	0.73	0.79	0.92	0.74	0.83	0.68	0.68	1.05	0.92	0.90
2064	0.88	0.86	0.88	0.88	0.81	0.78	0.86	0.84	1.00	0.77	0.85
2065	0.92	0.83	0.99	0.84	0.81	0.82	0.79	0.72	0.94	0.88	0.85
2067	0.88	0.82	0.82	0.79	0.80	0.85	0.77	0.79	0.95	0.76	0.92
2068	0.91	0.70	0.85	0.86	0.79	0.87	0.75	0.77	0.95	0.78	0.80
2069	0.90	0.79	0.77	0.97	0.74	0.85	0.82	0.79	0.97	0.79	0.81
206A	0.89	0.80	0.80	0.96	0.81	0.82	0.83	0.74	0.92	0.79	0.81

Star	Mg	H β	Fe492	Fe498	Fe50	Fe53	Fe54	Mg1	Mg2	Mgb	MgH
206C	0.95	0.89	0.78	0.99	0.74	0.83	0.74	0.84	1.01	0.81	0.91
206D	0.92	0.88	0.77	0.95	0.73	0.86	0.76	0.72	1.00	0.77	0.91
2071	0.87	0.77	0.83	0.81	0.72	0.81	0.78	0.80	0.95	0.74	0.86
2072	0.92	0.84	0.77	0.85	0.71	0.87	0.71	0.69	0.97	0.87	0.83
2073	0.92	0.76	0.89	0.76	0.79	0.83	0.81	0.82	0.91	0.79	0.78
2074	0.85	0.72	0.76	0.85	0.82	0.73	0.87	0.77	0.89	0.69	0.80
2078	0.94	0.81	0.79	0.90	0.76	0.94	0.81	0.79	0.98	0.77	0.95
2079	0.89	0.85	0.82	0.89	0.72	0.93	0.74	0.76	0.95	0.76	0.94
207A	1.06	0.88	0.79	1.09	0.70	0.93	0.76	0.78	1.18	0.89	1.04
207B	0.97	0.82	0.79	1.02	0.75	0.90	0.82	0.79	1.01	0.86	0.87
207C	0.91	0.85	0.75	0.88	0.75	0.82	0.79	0.82	0.94	0.78	0.87
207D	0.92	0.89	0.77	1.09	0.70	0.94	0.75	0.78	1.01	0.80	0.85
4003	0.83	0.95	0.81	0.95	0.89	0.92	1.05	0.78	0.86	0.79	0.96
4004	0.99	0.84	0.79	0.99	0.64	0.88	0.59	0.72	1.05	0.87	0.83
4005	1.01	0.98	0.63	0.95	0.66	0.97	0.77	0.76	1.07	0.92	0.97
4006	0.84	0.74	0.76	0.86	0.68	1.08	0.76	0.76	0.98	0.80	1.02
4007	0.77	0.90	0.87	1.17	0.66	1.04	0.58	0.60	0.67	0.80	0.53
400B	0.81	0.89	0.74	0.55	0.61	0.99	0.65	0.78	0.94	0.74	0.96
400C	0.79	1.00	0.83	0.37	1.01	1.28	0.55	0.77	0.88	0.58	1.09
4011	0.95	0.93	0.76	0.91	0.69	0.89	0.68	0.82	1.01	0.99	0.90
4012	0.92	0.66	0.74	1.07	0.61	0.90	0.62	0.88	1.13	0.84	0.90
4013	0.91	0.82	0.80	0.81	0.78	0.87	0.89	0.77	0.98	0.80	1.03
4014	0.97	0.86	0.94	0.81	0.70	0.92	0.68	0.80	1.04	0.92	0.94
4015	0.85	0.74	0.87	0.94	0.76	0.90	0.83	0.82	0.87	0.80	0.87
4017	0.89	0.95	0.77	1.02	0.69	0.83	0.74	0.81	0.98	0.77	0.97
4018	0.83	0.71	0.80	0.74	0.68	0.73	0.68	0.67	0.88	0.78	0.96
4019	0.85	0.68	0.87	0.78	0.70	0.93	0.82	0.73	0.95	0.77	1.01
401A	0.93	0.73	0.95	0.97	0.64	0.86	0.71	0.84	1.03	0.68	1.04
401B	0.88	0.93	0.83	1.23	0.71	0.84	0.66	0.65	1.08	0.71	1.02
401C	0.86	1.14	0.86	0.60	1.00	1.00	0.93	0.84	0.93	0.57	1.03
4021	0.88	0.80	0.74	0.88	0.68	0.83	0.69	0.70	0.88	0.90	0.84
4022	0.87	0.74	0.80	1.02	0.74	1.00	0.65	0.75	0.91	0.83	1.00
402B	0.83	0.89	0.67	0.90	0.81	0.91	0.93	0.83	0.83	0.75	0.87
4031	0.83	0.74	0.79	0.80	0.70	0.96	0.75	0.72	0.92	0.79	0.94
4032	0.67	1.14	0.54	0.77	0.72	0.84	0.77	0.71	0.67	0.64	0.83
4033	0.93	0.87	0.86	0.98	0.85	0.98	0.83	0.65	0.88	0.81	0.84
4034	0.96	0.91	0.83	0.94	0.71	0.84	0.70	0.77	1.01	0.91	0.97
4035	0.93	0.70	0.94	0.95	0.68	0.92	0.63	0.80	1.03	0.84	0.93
4036	0.96	0.91	0.76	1.11	0.57	0.88	0.60	0.74	1.07	0.92	0.99
4037	0.71	0.95	0.80	0.77	0.73	0.85	0.76	0.61	0.74	0.67	0.91
4042	0.92	0.59	0.80	0.81	0.74	0.76	0.90	0.83	0.96	0.79	0.81
4046	0.99	0.70	0.92	1.05	0.76	0.85	0.77	0.81	1.05	0.89	0.89
404B	0.86	0.32	0.95	1.02	0.66	1.06	0.50	0.91	0.98	1.15	1.00
404C	1.05	0.88	1.00	0.91	0.67	0.75	0.69	0.86	1.13	0.88	1.12
4054	0.95	0.75	0.67	1.06	0.49	0.75	0.41	0.71	1.23	0.83	1.17
4055	0.77	0.69	0.77	0.76	0.78	0.72	0.78	0.74	0.75	0.64	0.71
4056	0.99	0.72	0.75	0.73	0.89	0.79	0.92	0.76	1.01	0.82	1.02
4057	0.91	0.86	0.83	0.87	0.78	0.92	0.88	0.85	0.97	0.76	0.97
405A	0.82	0.78	0.83	0.85	0.58	0.80	0.58	0.73	0.93	0.86	0.91
405B	0.80	0.77	0.75	0.77	0.74	0.87	0.66	0.72	0.83	0.77	0.77
405C	0.94	0.81	0.97	1.11	0.84	0.86	0.92	0.71	0.96	0.72	0.82

Star	Mg	H β	Fe492	Fe498	Fe50	Fe53	Fe54	Mg1	Mg2	Mgb	MgH
405D	0.99	0.64	0.73	0.87	0.75	0.87	0.74	0.81	1.01	0.93	0.82
4061	1.00	0.77	0.76	1.08	0.66	0.81	0.64	0.79	1.07	1.02	0.89
4062	1.07	0.84	0.83	1.30	0.54	0.73	0.84	0.98	1.25	0.94	1.16
4063	1.01	0.72	0.85	0.81	0.74	0.82	0.68	0.66	1.00	0.88	0.82
4064	0.98	1.01	0.97	1.21	0.83	0.84	0.93	0.93	1.14	0.96	0.87
4065	0.85	0.81	0.97	0.78	0.85	0.85	0.83	0.74	0.84	0.82	0.83
4066	0.98	0.55	1.02	0.91	0.78	0.83	0.72	0.76	1.03	0.94	0.83
4067	0.95	0.83	0.83	0.71	0.79	0.83	0.77	0.86	0.98	0.85	1.05
4068	1.11	0.54	0.92	0.97	0.85	0.91	0.77	0.82	1.14	0.93	0.90
406A	1.03	0.77	0.80	1.06	0.84	0.92	0.90	0.77	1.04	0.89	0.83
406D	1.03	0.80	0.84	1.10	0.73	0.93	0.88	0.83	1.08	0.97	0.94
4071	0.96	0.82	0.86	0.93	0.64	0.89	0.77	0.84	1.04	0.87	0.89
4073	0.97	0.74	0.99	0.98	0.61	0.84	0.65	0.79	1.10	0.89	0.95
4077	0.92	0.66	0.79	0.92	0.64	0.80	0.67	0.76	0.99	0.87	0.82
4078	1.02	0.78	0.74	1.02	0.82	1.00	0.70	0.81	1.08	0.80	1.03
4079	0.81	1.11	0.93	0.93	0.67	0.94	0.69	0.92	0.87	0.78	0.92
407A	1.11	1.24	0.76	0.80	0.94	0.86	0.71	0.58	0.97	0.75	1.12
407B	0.90	0.71	0.86	0.91	0.73	0.82	0.78	0.77	0.99	0.78	0.93
407C	0.91	0.83	0.79	0.96	0.78	0.94	0.92	0.90	0.96	0.82	0.98

Table 6.2

PHOTOMETRY, VELOCITIES AND METALLICITIES

Star	R	R-I	B-R	V _r	Flag	Mg+2Fe
1003	15.85	0.97	1.93	134*	1	0.82
1005	15.52	0.95	1.58	-106	1	0.84
1006	16.00	1.01	1.58	-55	1	0.77
1007	15.54	0.92	1.86	87	1	0.85
1008	15.90	0.73	1.39	90	1	0.77
1009	16.01	1.02	1.97	36	1	0.84
1011	15.55	1.12	2.12	36	0	0.85
1012	15.89	1.05	2.07	18	0	0.81
1013	15.66	0.83	1.98	-16	0	0.85
1014	15.91	1.05	1.51	12	0	0.78
1015	15.86	1.05	1.79	68	1	0.77
1016	15.52	0.84	1.70	167	0	0.77
1017	15.96	1.15	2.09	-36	1	0.76
1018	15.61	1.33	1.83	68	0	0.83
1019	15.85	0.73	1.58	7	0	0.77
101A	15.87	1.19	2.08	-8	2	0.81
101B	15.83	1.01	1.72	98	2	0.77
101C	15.69	0.76	1.86	-73	2	0.81
1021	16.10	1.04	1.79	27	0	0.74
1022	15.56	1.06	1.85	50	0	0.85
1023	15.68	0.76	1.48	82	2	0.8
1025	15.92	0.78	1.70	4*	0	0.81
1026	16.02	0.81	1.94	-57	2	0.74
1027	15.69	1.11	1.91	-32	0	0.9
1028	15.88	1.27	1.63	45	2	0.74
1029	15.51	1.19	1.96	-90	2	0.84
102A	15.76	0.85	1.54	-75	2	0.8
102B	16.07	0.78	1.58	59	2	0.8
102C	16.01	0.79	1.56	-92*	2	0.78
1031	15.99	0.93	1.93	-18	1	0.82
1032	15.75	1.02	1.86	8	1	0.83
1033	15.62	0.78	1.80	5	1	0.79
1034	15.67	0.79	1.46	28	0	0.74
1035	15.57	1.35	2.30	35	0	0.83
1036	16.04	1.17	2.10	28	2	0.8
1038	15.88	0.95	1.45	51	2	0.77
1039	16.10	1.08	2.19	38	2	0.69
103A	15.56	0.90	1.65	50	2	0.8
103C	16.03	0.80	1.52	-8	2	0.81
1043	15.61	0.70	1.80	-175	1	0.94
1045	15.99	0.87	1.60	-148	1	0.98
1047	16.09	0.85	1.69	-210	1	0.76
1048	16.02	1.00	1.77	163*	1	0.81
104A	15.93	0.86	1.76	231	1	0.8
104B	15.76	0.75	2.02	41	1	0.78
1053	16.06	1.23	1.97	233	0	0.84
1056	15.74	0.81	1.43	25*	0	0.84
1057	15.79	1.55	2.05	40	0	1.13

Star	R	R-I	B-R	V _r	Flag	Mg+2Fe
1059	16.08	1.17	2.18	116	1	0.63
105A	15.70	0.79	1.68	6	1	0.83
105B	15.91	0.82	1.68	-44	1	0.84
105C	15.71	1.10	1.67	-67	1	0.93
105D	16.02	1.14	1.96	151	1	0.96
1061	15.65	0.83	2.11	-51	0	0.77
1062	15.78	0.94	1.96	51	0	0.93
1063	15.86	0.73	1.62	-95	0	0.91
1064	16.03	1.15	2.13	90	1	0.84
1065	16.06	0.91	2.02	128	1	0.63
1067	15.98	0.71	1.80	-88	1	0.86
1068	15.79	0.77	1.83	46*	1	0.81
1069	15.77	1.03	2.29	-3	1	0.96
106A	15.94	1.31	1.75	65	1	0.89
106B	15.97	0.75	1.62	-85	1	0.87
106C	15.53	1.16	1.92	-55	1	0.86
106D	15.82	0.75	1.88	23	1	0.85
1071	15.99	1.17	2.04	-228*	1	1.04
1072	15.94	0.94	2.00	-45	1	0.84
1073	16.04	0.89	1.80	-50	1	0.92
1074	15.87	1.11	2.14	-43	1	0.89
1075	16.00	0.86	1.47	70	1	0.96
1078	16.05	0.79	1.81	-111	1	0.81
1079	15.59	1.02	2.04	-29	1	0.81
107A	15.84	0.94	2.13	87	1	0.77
107C	15.59	0.76	1.66	132	1	0.82
107D	15.73	0.99	1.48	-111	1	0.71
2001	16.02	1.39	2.00	16	1	0.78
2002	16.02	1.01	1.54	133	1	0.78
2003	15.96	1.03	1.78	198	1	0.78
2004	15.94	0.93	2.00	88*	1	0.86
2006	15.99	0.88	1.74	-18	1	0.77
2007	15.85	0.95	1.72	-107*	1	0.76
2008	15.87	0.84	2.01	120	1	0.81
200A	16.07	1.00	1.79	7*	1	0.65
200B	15.71	0.96	1.92	166	1	0.68
200C	15.83	0.78	1.92	11	1	0.78
2011	15.84	0.81	1.93	109	0	0.81
2012	15.88	1.37	2.17	41	0	0.89
2013	15.63	1.19	2.21	13	1	0.81
2014	16.10	1.02	1.86	30	0	0.86
2015	15.97	1.01	2.03	49	0	0.78
2016	15.68	0.70	1.60	72	0	0.79
2017	15.85	0.84	2.00	40	0	0.81
2018	15.52	0.96	1.82	27	1	0.82
2019	15.73	1.12	2.13	-19	2	0.85
2066	15.98	1.19	1.65	40	0	0.94
201B	15.59	1.16	2.08	-102	2	0.85
201C	15.93	0.87	2.23	-134	2	0.74
2021	15.79	0.86	1.44	82	0	0.79
2022	15.65	0.99	1.83	101	0	0.8

Star	R	R-I	B-R	V _r	Flag	Mg+2Fe
2023	15.62	0.78	1.64	-56	0	0.84
2024	15.93	1.08	2.21	25*	0	0.77
2025	15.98	0.93	1.82	43	0	0.82
2026	15.87	1.17	2.19	118	0	0.83
2027	15.81	1.16	2.09	121	0	0.81
2028	15.61	1.38	2.13	53	0	0.88
2029	15.82	1.25	2.07	45*	2	0.77
202A	16.09	1.03	2.06	-92	2	0.73
202B	16.01	0.97	1.61	-19	2	0.84
202C	15.63	0.79	1.92	-130	2	0.77
2031	16.04	1.06	2.25	175	0	0.82
2032	16.10	1.08	2.26	190*	2	0.77
2033	15.91	1.07	2.04	13	0	0.83
2034	15.99	0.77	1.49	-56*	2	0.78
2035	15.89	0.89	1.65	-22	2	0.8
2036	16.08	1.46	2.15	42	2	0.76
2037	15.90	1.35	1.91	-4	2	0.65
2039	15.77	0.77	1.68	-24	2	0.67
203A	16.04	0.81	1.36	7	2	0.76
203C	16.06	1.10	1.60	-96*	2	0.82
2042	16.25	0.89	1.31	-3	1	0.79
2043	15.74	1.37	2.13	50*	1	0.83
2044	16.08	1.60	1.99	-161	1	0.98
2045	15.51	1.04	1.78	-125	1	0.96
2046	15.67	0.74	1.71	-4*	1	0.85
2047	15.99	1.15	2.02	-151	1	0.87
2048	15.72	1.18	2.14	59	1	0.81
2049	15.96	1.18	1.50	110	1	0.88
204A	15.54	0.92	1.45	9	1	0.84
204B	15.53	0.78	1.53	45	1	0.79
204C	16.00	0.72	1.71	-34	1	0.78
204D	16.02	0.84	1.57	-26	1	0.8
2051	15.66	0.87	2.20	49	1	0.81
2052	15.69	1.04	2.23	46	0	0.73
2053	15.79	0.95	1.91	-150	1	0.74
2054	15.58	0.76	1.58	-146	1	0.89
2055	15.98	0.82	1.72	74	1	0.77
2057	15.56	0.94	1.97	15	1	0.97
2058	15.78	0.89	1.59	9	1	0.88
2059	15.60	0.76	1.77	15	1	0.73
205A	15.67	0.81	1.75	71	1	0.8
205B	15.65	1.21	2.29	158	1	0.79
205C	15.87	1.01	2.06	-108	1	1.01
205D	16.00	1.35	2.14	184	1	0.93
2061	15.94	1.42	2.10	1	0	0.86
2062	15.76	0.72	1.59	-34	0	0.92
2063	15.74	0.94	2.11	74	1	0.93
2064	16.06	0.86	1.49	-58	1	0.87
2065	15.69	1.06	1.69	-86	1	0.75
2067	15.56	0.74	1.39	9	1	0.85
2068	15.85	0.76	1.57	-25*	1	0.82

Star	R	R-I	B-R	V _r	Flag	Mg+2Fe
2069	15.89	0.96	2.03	25*	1	0.91
206A	15.91	1.33	2.23	172	1	0.81
206C	15.55	0.94	2.13	-2	1	0.83
206D	16.03	0.72	1.72	-138	1	0.88
2071	15.61	0.92	1.98	-187	0	0.9
2072	15.86	1.09	2.16	-130	0	0.84
2073	15.75	0.98	1.83	-77	1	0.89
2074	15.88	0.98	1.74	-64	1	0.84
2078	15.76	0.93	1.48	41	1	0.79
2079	15.52	0.90	1.57	15	1	0.79
207A	16.03	1.24	1.90	-14	1	0.79
207B	16.04	0.96	2.04	-36	1	0.83
207C	15.77	0.84	1.99	79	1	0.85
207D	16.05	0.75	1.55	-52	1	0.78
4003	15.93	0.76	1.69	10*	1	0.64
4004	15.86	1.01	1.74	-124	1	0.95
4005	15.54	1.18	2.07	-64	1	0.92
4006	15.70	1.19	1.94	-23	1	0.83
4007	15.91	1.17	2.02	-256	1	0.89
400B	15.56	0.76	1.53	-57*	1	0.78
400C	15.90	0.88	1.97	132	1	0.6
4011	16.00	0.88	2.03	74	0	0.7
4012	15.93	1.12	2.10	151	0	0.87
4013	15.96	1.00	1.68	-141	0	0.79
4014	15.87	0.79	1.66	38	0	0.97
4015	15.67	0.74	1.66	3	0	0.8
4017	16.10	0.78	1.60	-82*	0	0.8
4018	15.94	0.91	1.49	-144*	1	0.93
4019	15.74	1.08	1.83	23	0	0.78
401A	16.02	1.01	1.85	248*	0	0.97
401B	15.89	1.03	2.14	-116	0	0.74
401C	15.77	0.96	1.98	85	1	0.81
4021	15.84	0.71	2.03	-77	0	0.81
4022	16.02	0.86	1.76	-81	0	0.85
402B	16.05	1.00	2.18	-76*	2	0.94
4031	15.75	0.76	2.14	-51	1	0.81
4032	15.74	0.83	1.54	-41	1	0.59
4033	16.04	1.21	2.07	-18	1	0.66
4034	15.98	0.84	1.84	-164	0	0.91
4035	16.05	0.85	1.73	19	2	0.81
4036	15.97	1.24	1.51	42	2	0.86
4037	15.79	1.15	1.69	-210	2	0.62
4042	15.57	0.86	1.93	60	1	0.79
4046	15.76	0.77	1.40	25	1	0.91
404B	15.88	0.72	1.70	46	1	0.63
404C	15.55	0.85	1.91	-62	1	0.85
4054	15.76	1.40	2.17	-47	1	1.14
4055	15.64	0.78	1.69	70	1	0.65
4056	16.04	0.94	1.78	-28	1	0.8
4057	15.74	0.77	1.54	68	1	0.89
405A	15.54	0.98	1.96	-70	1	0.7

Star	R	R-I	B-R	V _r	Flag	Mg+2Fe
405B	15.78	0.71	1.34	-101	1	0.8
405C	16.06	0.74	1.56	-83	1	1.02
405D	15.96	1.07	2.18	300*	1	1.
4061	15.52	0.78	2.01	-80	0	0.74
4062.	15.98	1.45	2.08	87	0	1.17
4063	15.83	0.81	1.62	24	0	1.01
4064	15.86	1.08	2.08	73	0	0.96
4065	15.81	0.72	1.76	-56	0	0.84
4066	15.99	0.91	1.93	-177	0	0.91
4067	15.85	0.78	1.49	-133*	0	0.82
4068	16.01	0.90	1.68	-49	0	0.87
406A	15.91	0.73	1.70	72	1	0.79
406D	15.80	0.84	1.83	-28	1	0.84
4071	15.63	0.99	2.20	14	1	1.05
4073	16.10	1.50	2.02	-78	1	1.08
4077	16.06	1.00	2.00	268	1	1.
4078	15.60	1.16	1.92	41	1	0.73
4079	15.68	1.17	1.78	-34	1	0.73
407A	16.09	0.90	1.99	-26	1	0.78
407B	15.61	0.79	1.80	-32*	1	0.64
407C	15.84	0.81	1.50	-56	1	0.86

Figure 6 shows the combined spectral index $Mg+2Fe$ *vs* color for the giants in the different regions of field F589: region 0 (squares), region 1 (crosses) and region 2 (triangles).

Figure 7 presents the final metal abundance values *vs* color for giants in regions 0 (squares), 1 (crosses) and 2 (triangles). This figure illustrates how different color cuts affect the final metallicity distribution for the samples in parts of the field with different reddening. The the most metal rich stars are excluded in the very reddened regions.

Finally, figure 8 shows the velocities *vs* $[Fe/H]$ for stars in different regions of field F589. The symbols are the same as in figure 8. The metallicities for the disk subgiants (triangles) are not real because the calibration is not valid for them, as discussed in the previous section. The rest of the giants, in the less reddened regions 0 and 1 show a trend with metallicity, in the sense that the most metal rich ones seem to be rotating more rapidly and have smaller velocity dispersions than the metal poor ones.

6.9. Contamination by Other Populations

6.9.1. The Disk

Based on IRAS maps, Habing *et al.* (1985) obtained an axis ratio of $c/a \sim 0.6$ for the bulge, while Harmon & Gilmore (1988) find $c/a \geq 0.7$. In addition, the COBE picture at $2 \mu m$ shows a similar flattening (e.g. Hauser et al. 1990). Assuming $c/a \approx 0.7$, we expect the density of bulge giants in the two fields

Figure 6.4 Radial velocities vs magnitude for the observed giants

Figure 6.5 Magnesium vs Fe5270+Fe5335 indices for the giants in the F589 window (regions 0, 1 and 2 correspond to a, b, and c, respectively).

Figure 6.6 Combined spectral index $Mg+2Fe$ vs color for the giants in the different regions of field F589: region 0 (squares), region 1 (crosses) and region 2 (triangles).

Figure 6.7 Final metal abundance values *vs* color for giants in regions 0 (squares), 1 (crosses) and 2 (triangles). This figure illustrates how different color cuts affect the final metallicity distribution for the samples in parts of the field with different reddening.

Figure 6.8 Velocities *vs* $[Fe/H]$ for giants in different regions of field F589. Symbols as in figure 8.

to be similar, and to be comparable to that in a minor axis field at $b = -10^\circ$ (Terndrup 1988; Blanco 1989; Blanco & Terndrup 1990). On the other hand, the density of disk stars in field 588 should be approximately the same as in a minor axis field at $b = 8^\circ$, while the number of disk stars in field 589 should resemble the number of disk stars present in Baade’s window. The available data (Terndrup 1988, Blanco 1989, Blanco & Terndrup 1990) suggest that $\sim 15\%$ of the observed giants in field 588 are expected to be disk stars, while $\sim 45\%$ is the corresponding figure for field 589. Note that the datasets on which these estimates are based contain mainly M giants. Since there is a metallicity gradient in the bulge (e.g. Terndrup 1988), the relative abundance of M stars would be enhanced in the inner fields by metallicity effects, we expect the actual disk contamination of our K giant samples to be less than 15% and 45% for fields 588 and 589 respectively.

The surface density of disk giants, however, must be much higher in F589 than in F588, due to the lower latitude of this field (2.7 compared with 7.6 degrees). This is confirmed by counting stars, where we estimate the disk contamination amounts to 35 % in this field as discussed in Appendix A.

Separating bulge and disk giants is not an easy task. Fortunately, we can use the reddening here. It is safe to assume that most of the stars in the reddened part of the field are disk giants. The bulge giants there would have been too faint to be included in our sample in large numbers. In that reddened field then, we are measuring the kinematics of mostly disk giants and subgiants in the direction of the bulge. There are 2 groups of stars that do not include any bulge giants:

the stars brighter than $R = 12.5$, and the stars in the very reddened regions of the field.

The reddening was determined with the aid of the IR photometry, and also by comparison to field F588. The reddening value for the window itself (stars with flag 0 in table 1) is fairly uniform with a mean value of $E(B-V) = 0.40 \pm 0.05$. The very reddened part of the field (flag 2 in table 1) has a much higher and variable reddening. We estimate $E(B-V) = 0.90 \pm 0.15$ for that region. The rest of the field (stars with flag 1 in table 1) has intermediate reddening values, $E(B-V) = 0.50 \pm 0.10$.

Figure A9 in Appendix A shows the expected density distribution of the different Galactic components along the line of sight for field F589. The magnitude cuts imply that different kinds of stars are going to be observed in these regions 0, 1 and 2. For example, a typical clump star with $M_R = -1$ lying at 8 kpc would be observed in the regions 0 and 1. Clump stars belonging to the old disk lying at 4 kpc would be observed in the regions 1 and 2. Subgiant old disk stars with $M_R = 1$ located at 4 kpc would be observed in regions 0 and 1 too, while regions 1 and 2 would include only subgiants at distances of about 2 kpc. Dwarf K stars would be included in all the regions, but their relative numbers with respect to the bulge giants would be insignificant, and much smaller in regions 0 and 1 than in region 2. These stars would be located within 0.3 kpc of the Sun, and despite their higher density, the volume sampled favors the inclusion of distant giants rather than nearby dwarfs.

In this field, we should carefully consider not only the density laws (figure A9) and the magnitude cuts, but also the color cuts. These color cuts determine

that stars of different metallicities will be included in the different regions. As the reddening increases, the color cuts will prevent the most metal rich stars from being included in the sample; the metal poor stars will be favored. This is the case for region 2, where we do not expect metal rich stars at all.

At the MX and MMT runs, we observed 26 bright stars with $R \leq 12.5$ in the F589 window (flag 0). This group has $\langle V \rangle = 74 \pm 13 \text{ km s}^{-1}$, and $\sigma = 64 \pm 9 \text{ km s}^{-1}$. These are mostly distant old disk giants. It is interesting to note here one of the differences between this low latitude field, and the higher latitude field F588. The bright giants in F588 have halo-thick disk kinematics. Instead, the bright stars in this low latitude field F589 are dominated by old disk giants rather than halo stars. Looking from the Solar position, the surface density of halo + bulge giants in both fields would be similar. However, the number of disk giants will increase by a factor of 5. Likewise, the bright giants in the M22 field follow halo kinematics. However, a direct comparison with the M22 field would be risky due to the different selection criteria for the sample.

In the very reddened part of the field, region 2, we observed 31 stars at LCO with $12.5 \leq R \leq 13.2$. These stars are divided in two groups, stars redder and bluer than $(B-V)_0 = 0.80$, respectively. The stars with $(B-V)_0 \geq 0.80$ should be the same type of stars as the bright stars considered before, because accounting for the reddening vector, they will occupy the same region of the CMD. This is confirmed by the kinematics: for the 15 stars with $(B-V)_0 \geq 0.80$ we find $\langle V \rangle = -21 \pm 20 \text{ km s}^{-1}$, and $\sigma = 76 \pm 14 \text{ km s}^{-1}$. These stars include old disk giants, but would have lower metallicities in the mean than the sample of bright

giants, because the reddest stars were not observed. However, the 16 stars with $(B-V)_0 \leq$ have $\langle V \rangle = -2 \pm 12 \text{ km s}^{-1}$, and $\sigma = 48 \pm 9 \text{ km s}^{-1}$. These are mostly closer subgiants of the old disk, and are not going to be present in the unreddened regions 0 and 1. These stars have $H\beta$ stronger in the mean. They represent the pure disk kinematics, consistent with the local K and M dwarfs that have $\sigma = 29 \text{ km s}^{-1}$ (Wielen 1977).

In the unreddened part of the field we can use these disk values to obtain the real bulge kinematics. From the values given above, we will adopt $V_m = 74 \text{ km s}^{-1}$, and $\sigma = 64 \text{ km s}^{-1}$ for the disk (the MX and MMT values are preferred here because they give more accurate velocities), and will discount that contribution from the kinematics of the total sample. For that, we have to decide the relative numbers of disk to bulge and halo stars present in regions 0 and 1. There are two ways to estimate that: 1) count the number of disk stars present in the reddened part of the CMD that would fall in the observed region when reddening is accounted for, and 2) adopt a Galaxy model. The first approach is harmed by the fact that the APM machine does not yield a complete sample for the field, only the stars that meet restricted criteria of roundness and proximity in the three colors are included, and this is certainly a function of reddening because the crowding changes. The second approach, discussed in Appendix A, depends on the assumption of several different parameters, which are uncertain.

Given those caveats, both alternatives will be followed to estimate the pure bulge kinematics. For the first approach, we simply count stars in the CMDs like the ones showed in figure 2. Then we scale these number counts to the

relative areas, and account for the fact that the reddened and unreddened regions have different mean latitudes. For that last step we assume an exponential surface density law with scale-height 300 pc (~ 2 degrees). We obtain that $N_{disk}/N_{bulge} = 0.32$ for the unreddened parts (regions 0 and 1).

For the second approach (considered in Appendix 1), we need 7 structural constants to estimate the different relative contributions, some of which are really not so well known. These constants are distance to the Galactic center $R_\odot$, the power law exponent n for the bulge density law, the power law exponent m for the halo density law, the disk scale height h_z and scale length h_r , the thick disk scale height H_z and scale length H_r . We also need normalization factors at some distance for the halo, bulge and thick disk with respect to the thin disk, and the absolute density of disk giants at that distance.

All of the structural constants and normalization factors needed imply that the results would be heavily model dependent. For example, Terndrup (1988) and Rich (1988) estimate from simple Galactic models that the bulge greatly outnumbers the disk component in the inner 1.5 kpc. However, Ruelas-Mayorga & Teague (1992) come to completely different conclusions, arguing that the disk contamination is very significant, even at 0.5 kpc from the Galactic center. The discrepancies are due merely to the different structural parameters adopted by these authors. One of the advantages of the present study is that we are able to use several fields located at different places with respect to the Galactic center and plane to constrain the models.

As listed in table 2 of Appendix A, the model expects for field F589 that the relative numbers of bulge : halo : thick-disk :thin-disk are 45 : 15 : 2 : 35. Again, these values are not very well defined.

An important point raised by Ruelas Mayorga & Teague (1992) is that the relative disk/bulge contribution for the bulge fields will be a function of magnitude, the number of disk giants decreasing with respect to the bulge giants with increasing magnitude. This is also why it is important to observe giants as faint as possible.

The cuts in the colors and magnitudes that defined the selection of the sample were designed to avoid including nearby disk dwarfs. However, some might have been selected anyway, and we have to discuss their possible influence. Furthermore, as we have seen in chapter 4, the bulge giants have strong Mg absorption, that prevents us from using the strength of the Mg bands to eliminate disk dwarfs. The mean velocity of nearby dwarfs (and fainter subgiants) can be taken to follow $V_r = A d \sin(2l)$, and $V_\phi = d (A \cos(2l) + B)$ (e.g. Oort 1927, Mihalas & Binney 1981), where d is the mean distance in kpc, $A = 15 \text{ km s}^{-1}$, and $B = 11 \text{ km s}^{-1} \text{ kpc}^{-1}$. For field F589 at $l = 12$, the dwarfs have $V_r = 6.1 d \text{ km s}^{-1}$, and $V_\phi = 25.1 d \text{ km s}^{-1}$. Neglecting the latitude effect ($b = 3$ is very small), we see the the mean line of sight velocity for nearby dwarfs is going to be close to 0 km s^{-1} . The observed velocity dispersions for K and M dwarfs in the Solar neighborhood are $\sigma_{los} = 29 \text{ km s}^{-1}$ (Wielen 1977).

These values imply that for a relatively small contamination by nearby dwarfs, they would not have a significant effect on the kinematics. Note that

this is very different than the halo case, where contamination by a few halo giants would bias the results due to the high σ and low V_{rot} . Fortunately, the metallicity helps discriminate halo giants.

6.9.2. The Thick Disk

The number of metal poor thick disk (mptkd) giants with respect to the number of halo giants is estimated using the normalization in the Solar neighborhood given by Morrison (1993) $N_{mptkd} / N_{halo} = 2$ (note that this value is higher than previous estimates). The model discussed in Appendix A is used. Figure A9 plots the computed numbers of thick disk and halo stars versus distance. The halo outnumbers the metal poor thick disk by a factor of ≥ 50 . These estimates change according to the parameters used. For example, if we change the scale-length of the thick disk to 4.4 kpc (value preferred by Lewis & Freeman 1989 for the disk) the relative number thick disk giants would be more insignificant. Therefore, we are confident that we are measuring halo kinematics for the lowest metallicity bins.

However, for intermediate metallicities ($[Fe/H] \sim -1.0$), a few thick disk stars may be present if the thick disk normalization is increased as Morrison (1993) proposes. In these intermediate bins the transition between halo and bulge kinematics is blurred by the presence of thick disk giants.

We expect $\sigma_{los} \approx 80 \text{ km s}^{-1}$ for local thick disk giants in the direction of F589 (after Carney et al. 1990, Norris & Ryan 1992). The run of the thick disk velocity dispersion with Galactocentric distance is not known. Assuming a

similar behavior as the thin disk (taken from Lewis & Freeman 1989), the thick disk velocity dispersion yields unreasonably high values ($\sigma \geq 200 \text{ km s}^{-1}$) at 1.7 kpc from the Galactic center.

6.10. Kinematics of Different Components

6.10.1. Halo Kinematics

If we want to study the bulge, accounting for the halo is not a problem, because as we have seen in other different fields, the bulge and halo have different metallicities. If we consider only stars more metal rich than $[\text{Fe}/\text{H}] = -1.0$, most of the halo stars will be excluded.

To obtain pure halo kinematics in this field, we consider the stars with $[\text{Fe}/\text{H}] \leq -1.5$. There are 20 giants with these metallicities, that have $\langle V \rangle = 24 \pm 24$, and $\sigma = 107 \pm 17 \text{ km s}^{-1}$. These values are consistent with the halo kinematics in the other bulge fields studied, M22, F588, and BW.

The 47 giants in the next metallicity bin, with $-1.5 \leq [\text{Fe}/\text{H}] \leq -1.0$, have $\langle V \rangle = 80 \pm 15$, and $\sigma = 101 \pm 10 \text{ km s}^{-1}$. Although this bin is dominated by halo giants, there is some indication of a transition to a kinematically colder system, due to contamination from a few bulge or disk giants.

The halo kinematics in field F589 are significantly different from the kinematics of the rest of the population in this field.

6.10.2. Disk Kinematics

The only kinematic study of the inner disk is that of Lewis & Freeman (1989). They find that the radial component of the disk velocity dispersion increases towards the Galactic center, from $\sigma_r = 30$ km/s at the Solar position to $\sigma_r = 95$ km/s at 0.5 kpc. They fit an exponential law to σ_r , with scale-length $h_r = 4.4$ kpc (for $R_\odot = 8.5$ kpc). Unfortunately, Lewis & Freeman (1988) did not divide their sample into different Galactic components, and it is possible that some of their giants belong to the thick disk, halo or bulge rather than the old thin disk.

There are two common choices for the radial dependence of the velocity dispersion in the Galactic disk used in the literature. One is the constant anisotropy model, and the other is the constant Toomre Q-parameter model (e.g. Cuddeford & Amendt 1992).

In the constant anisotropy model, σ_r has an exponential radial profile for the Galactic disk with exponential luminosity profile and constant scale-height h_z . This is the model preferred by Lewis & Freeman (1989), and it is also a good description of the behavior of other spirals (e.g. van der Kruit & Freeman 1986). Cuddeford & Amendt (1992) argue that the constant anisotropy model is a good approximation for the inner Galactic disk, while the constant Toomre Q parameter model is a good approximation for the outer Galactic disk.

In the constant Toomre Q parameter model, the radial dependence of the disk velocity dispersion is given by $\sigma = r^2 \exp(-2R/h_r)$, for a flat rotation curve (e.g. Cuddeford & Amendt 1992).

Recently, Bottema (1993) analyzes a large sample of spiral disks, confirming that σ_r in other spirals behaves like σ_r in the Milky Way, i.e. decreasing with distance from the center, and an exponential provides a good description of the data.

The lack of a good distance estimator prevents us from repeating Lewis & Freeman's (1989) analysis for our sample. However, some interesting comparison can be made. According to Lewis & Freeman (1989), the old disk velocity dispersion at 1.7 kpc from the Galactic center would be $\sigma_r \sim 86 \text{ km s}^{-1}$. The behaviour of the disk velocity ellipsoid as function of distance is not known. Assuming isotropy ($\sigma_r/\sigma_\phi = 1.0$) and the local value ($\sigma_r/\sigma_\phi = 1.4$), at the tangent point of F589 the disk will have $\sigma_\phi = 86$ and 61, respectively. A density weighted integration of the disk kinematics from Lewis & Freeman (1990) along the line of sight yields $\sigma_{los} = 74$ and 53 for both cases $\sigma_r/\sigma_\phi = 1.0$ and 1.4, respectively.

Also, for a flat rotation curve with $V_{rot} = 220 \text{ km s}^{-1}$, we would observe $\langle V_{los} \rangle = 129 \text{ km s}^{-1}$ for the disk component in this field (integrated between 4 and 12 kpc). Thus, according to our estimate of disk contamination given in Appendix 1, about 40% of the stars with $[\text{Fe}/\text{H}] \geq -1.0$ would have $\sigma = 74$ and 53 for both cases considered above, and $\langle V_{los} \rangle = 129 \text{ km s}^{-1}$. This velocity dispersions are close to the observed value $\sigma = 70 \pm 5 \text{ km s}^{-1}$, but the observed mean velocity $V = 85 \pm 7 \text{ km s}^{-1}$ is smaller than that predicted for the disk. This leads to the conclusion that perhaps disk contamination is not very important, and that the great majority of giants observed in this field belong to the bulge.

Furthermore, the oblate isotropic rotator bulge model of Kent (1992) predicts observed $\sigma_{los} = 65$ and $\langle V_{los} \rangle = 90 \text{ km s}^{-1}$ for field F589 (Kent, private communication), remarkably close to the observed values. If there were significant disk contamination, we would observe a higher mean velocity in this field.

However, the kinematics of the disk in the inner Galaxy remain poorly determined, because the mean offset from the properties of bulge stars is much less than the dispersion in these quantities.

6.10.3. Bulge Kinematics

To obtain "pure" bulge kinematics in this field, first we should select stars with $[\text{Fe}/\text{H}] \geq -1.0$. Then, we should subtract the disk contribution, given by a gaussian distribution with $\langle V \rangle = 129$ and $\sigma = 64 \text{ km s}^{-1}$ scaled to account for 35 % of the total number of stars. The particular selection of the dispersion is from the 26 bright disk giants in F589, which also happens to be the mean of the predictions of the Lewis & Freeman disk for the cases where $\sigma_r/\sigma_\phi = 1.0$ and 1.4. This particular way of subtracting the "disk" would bring the "bulge" mean velocity down from the observed value $\langle V \rangle = 85 \text{ km s}^{-1}$. However, there are not many stars with such high observed velocities in this field. If we were to subtract a gaussian with the above mentioned parameters from the observations, the resulting velocity distribution would become negative for velocities higher than $\sim 100 \text{ km s}^{-1}$. Thus, we cannot clearly separate the bulge from the disk in this field, and we will take the sample as a whole when studying the kinematics, with the caveat that disk contamination is present.

Therefore, it is not possible to obtain the mean velocities and velocity dispersion of "pure" bulge giants as function of metal abundance as we did in F588 because of the heavy contamination from the other Galactic components. However, there is a strong trend of the kinematics with metallicity in field F589. Table 3 lists the mean velocities and velocity dispersions for bins of different metallicity. Figure 9 shows the dependences on metallicity of the mean Galactocentric velocity, velocity dispersion and local degree of rotational support. The dependences seen in figure 9 are similar to those found in the other fields studied.

Finally, figure 10 shows the radial velocity distributions for different metallicities. No clear structure is seen in these distributions that would allow us to associate different peaks with the bulge or the disk.

6.10.4. The M Giants

The M stars in this field, although not very numerous, follow the disk kinematics. The mean velocity and velocity dispersion are $V_m = 44.3 \pm 20$ km s⁻¹, and $\sigma = 75 \pm 14$ km s⁻¹ for a total of 14 early M giants observed in field F589.

An interesting point is that Sharpless et al. (1990) found that the brightest M giants in Baade's window have a much smaller velocity dispersion than the bulk of the M giants. They analyze a large sample of over 200 M giants, and found no other kinematic trend with metallicity, color or line strength. The 14 M giants with $I \leq 11.8$ in the sample of Sharpless et al. (1990) have $\sigma = 71.3 \pm 17$

Table 6.3: KINEMATICS VS METALLICITY IN THE FIELD F589

[Fe/H]	N	mean	err	stddev	err	V+65/sig
[< -1.5]	20	-43	24	107	17	0.203
[-1.5 to -1.0]	47	5	15	102	10	0.688
[-1.0 to -0.5]	84	4	10	93	7	0.739
[-0.5 to 0.0]	43	19	13	86	9	0.979
[0.0 to +0.5]	27	17	14	72	10	1.149
[> +0.5]	19	22	17	76	12	1.146
[B-V ₀ > 0.80]	15	-21	21	82	15	0.542
[B-V ₀ < 0.80]	16	-2	14	56	10	1.116
[bright *s]	26	9	13	65	9	1.142
[M giants]	14	44	22	82	15	1.340

Figure 6.9 Mean Galactocentric velocities (a), velocity dispersions (b), and degree of rotational support (c) as function of metallicity for giants in regions 0 and 1 of field F589.

Figure 6.10 Distribution of velocities for giants of different metallicities in the field F589.

km s⁻¹. This value is not very similar to the velocity dispersion of the bright giants in F589, $\sigma = 40 \pm 20$.

6.11. Conclusions

We have succeeded in separating the halo from the bulge and disk components in the low latitude field F589.

The halo, represented by the most metal poor stars, behaves as found in the fields F588 and M22, with low rotation and high velocity dispersion. The halo is kinematically decoupled from the bulge in field F589, as was found in the other fields.

The bulge here also shows similar kinematics as the fields studied in chapters 4 and 5, even though the interpretation of the kinematics trends with metallicity is more complicated in field F589 due to high disk contamination.

7. KINEMATICS AND STELLAR POPULATIONS OF THE GALACTIC BULGE: IMPLICATIONS FOR GALAXY FORMATION

7.1. Introduction

In chapters 4, 5, and 6 we were able to derive the mean velocity and velocity dispersion of the K giants in each field (F588, M22 and F589) as a function of metallicity. In this chapter we will put together all of this information into a coherent picture. We will then compare these results to those of similar studies already in the literature. We then look at other kinematic tracers and see if we can understand to what different stellar populations they should be associated, remembering that each of the dominant Galactic components, halo, bulge and disk is likely to be reaching an unknown peak density at or near the Galactic center. These populations were defined in chapter 1 and in appendix 1. Then we review the possible scenarios of chemical evolution of the bulge, and the existence of a metallicity gradient. Finally, armed with all the existing evidence, we discuss our preferred scenario of bulge formation, and argue that the inner metal rich globular clusters are associated with the bulge.

7.2. Halo Kinematics as Function of Position

The kinematics of the halo population in the Solar neighborhood are described in the recent compilations of Norris & Ryan (1992) and Ryan & Norris (1993), (see appendix 1).

One observational fact not often appreciated is that the global halo kinematics –as measured by the halo globulars– are similar to the local halo kinematics –as measured from the metal poor stars in the Solar neighborhood– (e.g. Frenk & White 1980). This suggests that the halo kinematics do not change appreciably with position in the Galaxy.

Frenk & White (1980) showed that a constant rotation velocity is a good description for the halo system of globular clusters. In contrast with this, Morrison & Harding (1993) claim that the globular cluster data show evidence for the halo rotation to increase towards the Galactic center. Freeman (1987) reviews the evidence that the Galactic halo is isothermal. Pier (1984) finds that the line of sight velocity dispersion of halo AB stars remains constant between 3 and 12 kpc from the Galactic center. Norris (1986) analyzes the question of angular momentum of the halo as function of Galactocentric distance. Using non-kinematically selected samples, he also finds little variation of the mean line-of-sight velocity V_{los} and velocity dispersion σ_{los} with R_{Gal} for the 7–50 kpc range. However, the results of Norris (1986) could change if one adopts a different metallicity limit to define the halo stars, following the findings of Morrison et al. (1990) that some of the metal poor stars at intermediate Z distances belong to the thick disk rather than the halo.

However, the kinematics of any halo population extending into the inner 2 kpc of the Galaxy are not known. With the addition of such data, new limits can be placed to constrain the dynamical models for the halo, which make different predictions for the velocity dispersion in the inner kiloparsecs (e.g.

White 1985, Levison & Richstone 1986, Sommer-Larsen 1987). To extend the results of Norris (1986) and Pier (1984) into the inner halo, we consider here the data of Rich (1990) in Baade's window, our data in the fields F588, F589, and M22. All these 4 fields are contained within the IRAS and COBE bulge. We will also include the data of Harding (1990) in field at $l, b = (10, -22)$, and the data of Morrison & Harding (1993) in a field at $l, b = (-10, -10)$. These fields are outside of the bulge apparent in IRAS and COBE maps.

Morrison & Harding (1993) present preliminary results for a large sample of giants in a field at 2 kpc projected distance from the center, with metallicities determined from Washington photometry. By dividing the sample according to metal abundance they are able to distinguish kinematic groups consistent with halo and bulge populations.

The field located at $l, b = (10, -22)$ of Harding (1990) is dominated by the halo and thick disk according to the models of Appendix 1, and we take it to represent halo kinematics. On the other hand, the field of Harding at $l, b = (14, -14)$ requires a large correction to be applied, because the sample does not reach the tangent point (Harding 1990). The halo still dominates here, but there is more contamination from the bulge (because it is flattened), and from the disk components. This is a transition field, not representative of the bulge itself. It is difficult here to discriminate the different components with only 43 stars and no metallicity information. Furthermore, the more recent data of Morrison & Harding (1993), at a field located in a similar position but in a different quadrant supersede the data of Harding (1990) in the $(14, -14)$ field. Therefore,

this field will not be considered, we prefer the values of Morrison & Harding (1993) instead.

Rich (1990) presents radial velocities and metallicities for 53 K giants in Baade's window. Even though he divides the sample according to metallicity and finds that the metal poor giants have higher velocity dispersions (suggesting that the kinematics of the metal poor giants are consistent with membership in the halo), the division is arbitrary, and is not taken to represent the bulge and halo populations. Shifting the abundances of Rich (1990) to the scale presented by McWilliam & Rich (1993) and Smith & Plez (1993), 11 stars are more metal poor than $[\text{Fe}/\text{H}] = -1$. Most of these would qualify as halo giants according to our definition based on abundance. The majority of the remaining 42 giants belong to the bulge itself, with a minimal 5% contamination from disk giants (Rich 1990). We find that the mean Galactocentric velocity and velocity dispersion for these 11 low metallicity giants are $V_m = 8.4 \pm 41.4 \text{ km s}^{-1}$, and $\sigma = 137.3 \pm 29.3 \text{ km s}^{-1}$, respectively. Based on both metallicity and kinematics we can identify them with the halo population. These values are consistent with those found for the RR Lyraes, which have $[\text{Fe}/\text{H}] \sim -1$ in the mean (Walker & Terndrup 1991) and $\sigma = 130 \pm 19 \text{ km/s}$ (Gratton 1987, Tyson 1991). It therefore seems sensible to associate the RR Lyraes with the halo rather than with the bulge. For the 42 bulge giants $V_m = -25 \pm 14 \text{ km/s}$, and $\sigma = 96 \pm 10 \text{ km/s}$ at BW, quite different from the most metal poor stars.

In the case of the inner fields studied here, the projection effects determine that $\sigma_{los} \approx \sigma_\phi$. This is not true for Baade's window, where $\sigma_{los} \approx \sigma_r$, or for

the fields studied by Norris (1987). However, Norris gives the different velocity dispersion components, so we study σ_ϕ as function of R_{Gal} . If the shape of the velocity ellipsoid of the halo is independent of R_{Gal} , then $\sigma_r = 1.4\sigma_\phi$ (c.f. Appendix 1).

Figures 1 a and 2 a show the run of σ_ϕ with distance from the Galactic center for both the metal poor and metal rich components, which we identify with the halo and bulge of the Galaxy. These two components again have clearly distinct kinematics. Thus, the results of Norris (1986) can be extended into the inner halo. That is, there appears to be no strong dependence of velocity dispersion with distance, for the metal poor halo. The inner halo also appears to be well fitted by a constant rotation. This explains why the *global* kinematics of the halo globulars are indistinguishable from the *local* kinematics of the halo subdwarfs in the solar neighborhood (Frenk & White 1982, Zinn 1985).

Frenk & White (1980) predict $\sigma_r = 118$ for their isotropic models ($\beta = 0$), and $\sigma_r = 133$ for their anisotropic models ($\beta = 0.7$) for these fields. Our findings are consistent with the latter models.

In conclusion, the available evidence is consistent with the hypothesis that there is no substantial overlap between the halo and the bulge components in abundance or kinematics in the inner regions of the Galaxy (We cannot say anything about an overlap in age). However, for the old disk and bulge there might be a significant overlap in metallicity and kinematics. These two components cannot be separated until the behavior of the inner disk is better understood. Note that the Galaxy is the only spiral we can dissect in detail,

Figure 7.1 a) Run of the mean line of sight velocity v vs Galactocentric distance projected in the plane for halo giants in different fields. b) Run of mean ϕ velocity v vs Galactocentric distance projected in the plane for halo giants in different fields. c) Velocity dispersion σ_ϕ vs Galactocentric distance for halo giants.

separating different components. In more distant galaxies these components are blended into the integrated light. The assumptions made to separate these properties should be in a more firm footing once we know the relative contributions of the different components of the Milky Way.

To come to these conclusions, it was necessary to consider fields other than Baade's window, because –as we shall see in the next section–, the bulge velocity dispersion increases towards the center, determining that at Baade's window the halo and bulge have similar velocity dispersions. Furthermore, at Baade's window we do not have the benefit of rotation information to discriminate further these two components.

7.3. Bulge Kinematics as Function of Position

7.3.1. Bulge K Giants

In chapter 4 we showed that the velocity dispersion of bulge K giants depends on metallicity as well as on Galactocentric distance (Minniti et al. 1992). We will reanalyze our results combined with the data from Rich (1990) at Baade's window, and preliminary data from Morrison & Harding (1993) at $l, b = (-10, -10)$.

Figure 2 a shows the run of velocity dispersion with Galactocentric radius for bulge K giants. These measurements confirm the results of Minniti et al. (1992), and are in excellent agreement with the preliminary results of the large scale survey by Terndrup (1993). We assume that the velocity dispersion can be approximated by the functional form $\sigma = \sigma_0 (r^2 \sin^2 \theta + r^2 \cos^2 \theta / \epsilon^2)^{-m/2}$ (c.f.

Figure 7.2 a) Run of the mean line of sight velocity *vs* Galactocentric distance projected in the plane for bulge giants in different fields. The dashed line is the fit to the Miras (Menzies 1990), and the dashed lines is the fit to the planetary nebulae (Kinman et al. 1988). b) Run of mean ϕ velocity *vs* Galactocentric distance projected in the plane for bulge giants in different fields. c) Line of sight velocity dispersion *vs* Galactocentric distance (corrected for flattening $\epsilon = 0.3$)

Appendix 1) for the range of distances considered here, with $\epsilon = 0.3$. From figure 2 a we derive the value for the exponent of the velocity dispersion law of the Galactic bulge: $m = 0.35 \pm 0.05$. In contrast, the halo has $m = 0.0 \pm 0.05$, significantly different than the bulge. In comparison, Minniti et al. (1992) obtain $m = -0.33$ for the whole population. Recently, Terndrup (1993) reviews the kinematics of the whole population, including his unpublished results. Aside from the fact that he puts all fields on the same footing (i.e. does not take into account the flattening of the bulge), he finds a similar behavior for the velocity dispersion, with exponent $m \sim 0.4$. This behavior of the velocity dispersion is fully consistent with the models of Kent (1992).

Now we will consider the rotation of the bulge. There are two simple alternatives to describe the observations: by using a solid body rotation, or by assuming constant rotation (zero rotation is ruled out). In the solid body rotation case, we have $V_{los} = V_\phi$ to a very good approximation for the fields considered here. In constant rotation, we have to integrate V_{los} weighted by the density as function of distance to obtain V_ϕ . For the different fields studied here we find:

$$V_\phi^{F588} = 1.27 \langle V_{los} \rangle$$

$$V_\phi^{F589} = 1.17 \langle V_{los} \rangle$$

$$V_\phi^{M22} = 1.23 \langle V_{los} \rangle$$

$$V_\phi^{MH} = 1.25 \langle V_{los} \rangle$$

$$V_\phi^{BW} = 2.43 \langle V_{los} \rangle$$

where we have used the bulge density law from Appendix 1 and the Monte–Carlo simulations. These are also valid for the halo, which has a similar density law.

The same applies for the velocity dispersions, although these are also dependent on the shape of the velocity ellipsoid. Since the velocity ellipsoid of the bulge is nearly isotropic (e.g. Spaenhauer 1992), we make this assumption to get $\sigma_\phi = \sigma_{los}$, which is correct to 2 % for the fields studied here.

However, for the halo these coefficients are different, because it has an anisotropic velocity ellipsoid, as seen in the previous section. Choosing the axis ratios for the halo according to Appendix 1, and assuming that the halo velocity ellipsoid does not change shape significantly inside 8 kpc, we find $\sigma_\phi = \sigma_{los}$ within 2% for all fields except for BW, where $\sigma_\phi^{BW} = 0.85\sigma_{los}$.

The ϕ components of the mean velocity and velocity dispersions plotted in figures 1 and 2 have been computed using these relations for the halo and bulge. In particular, in figure 1 we have added data from Morrison (1993), Norris (1987), Norris & Ryan (1992), and Morrison & Harding (1993).

Figure 2 shows that the bulge is better described by a solid body rotation than by constant rotation. This is another piece of evidence in favor of the bulge being a separate entity from the halo, which is well fitted by a constant rotation model. The rotation curve of the bulge is also different from the disk rotation curve, as given by the HI and CO measurements (e.g. Burton 1976, Burton & Gordon 1978). Thus, the bulge and the disk are also separate entities.

We note that in the case of the bulge, these dependences on kinematics on distance from the Galactic center could be interpreted as a latitude dependence

also, since F588 and the field of Morrison & Harding (1993) are at higher latitude than Baade's window and F589. More fields at different Galactic longitudes and latitudes are needed to discriminate a radial dependence from a latitudinal dependence of the kinematics. In the same way, a number of fields are needed to decide if a spherical or a cylindrical system better describe the bulge kinematics. This would be accomplished also with the determination of proper motions towards bulge windows.

A word of caution is in order about comparing different samples: even in BW, the field more thoroughly studied, the mean velocities of the different samples are not in good agreement with one another, as can be seen in table 1. In particular, most of the tracers give a negative mean velocity for $l = 0$, as noted by Tyson (1991). Also note that if the inner Galaxy has a bar, streaming motions might be present. One should then be very careful when comparing different fields. Whenever possible, the same tracers should be used.

Finally, figure 3 shows the relationship between rotation parameter V/σ and ellipticity ϵ for coaxial oblate spheroids with different anisotropy δ (solid lines), reproduced from Binney & Tremaine (1987), after the models of Binney (1978). Here, V_m is the maximum rotation, and σ_0 is the velocity dispersion at the center of the potential. From above, we have for the halo $V_m = 25 \pm 15 \text{ km s}^{-1}$, and $\sigma_0 = 135 \pm 10 \text{ km s}^{-1}$, and for the bulge $V_m = 105 \pm 10 \text{ km s}^{-1}$, and $\sigma_0 = 115 \pm 10 \text{ km s}^{-1}$. The ellipticity $\epsilon = 1 - b/a$ is for the bulge $\epsilon = 0.35 \pm 0.05$ (e.g. Kent et al. 1991, Habing et al. 1985, Harmon & Gilmore 1989). Bahcall (1986) reviews the determinations of the values of halo flattening, concluding

Figure 7.3 Relationship between rotation parameter V/σ and ellipticity ϵ for coaxial oblate spheroids with different anisotropy δ (solid lines), reproduced from Binney & Tremaine (1987, their figure 4-5 in p. 217). We have plotted the location of the Galactic bulge (filled circle) and halo (open circle), along with their respective error bars.

$b/a = 0.2^{+0.2}_{-0.05}$. Freeman (1987) also reviews a number of different flattening determinations for the halo, suggesting that it might be flatter inside 8 kpc (see also discussion by White 1989). However, previous studies have not made the distinction between bulge and halo clear. We take $\epsilon \sim 0.3$ for this component, noting that it could be as high as 0.5. The axis ratio σ_ϕ/σ_r of the local halo velocity ellipsoid would give $\epsilon \sim 0.35$.

We have plotted in figure 3 the location of the Galactic bulge (filled circle) and halo (open circle), along with their respective error bars. This figure shows that the bulge is indeed supported by rotation, lying in the place occupied by bulges of typical spirals, while the halo is supported by velocity anisotropy, lying in the region occupied by most elliptical galaxies (e.g. Binney 1982). This figure also shows that the bulge velocity ellipsoid is nearly isotropic, consistent with the results from Spaenhauer et al. (1992). The range of possible anisotropies is wider for the halo, mostly due to its uncertain flattening. The lesson of this figure is that one has to separate the halo from the bulge giants when modeling the proper motions towards the bulge (e.g. Spaenhauer et al. 1992).

7.3.2. Bulge M Giants

The M giants are easy to find in the bulge windows using objective prism spectra (Nassau & Blanco 1958, Blanco 1965, Blanco, McCarthy, & Blanco 1984). They are very luminous and have very sharp TiO band-heads, making it possible to obtain good velocities with short exposure times. It is then natural that most of the kinematics of the Galactic bulge fields have been done using

these stars, as seen in table 1. However, unlike the K giant phase, not all the old stars go through the M giant phase of evolution. Studying only M giants one could miss a large fraction of the metal poor population, which may or may not be important in these windows.

Previous velocity determinations for M giants in bulge fields are listed also in table 1. Mould (1983) obtains velocities for 49 giants in Baade's window from the Blanco survey, finding $\sigma = 113 \pm 11$. These results are confirmed by the larger (225 M stars) sample of Sharpless et al. (1990), also selected from the Blanco survey. Rich (1990) finds $\sigma = 104 \pm 10$ based on 53 K giants. Finally, Terndrup is working on a monumental survey (e.g. Terndrup 1993) of M giants in the bulge.

The same check of kinematics *vs* metallicity could be applied to the samples of M giants, but it is more difficult to determine reliable abundances. Sharpless et al. (1991) find no significant trends of the velocity dispersion with TiO or CaII strength in their large sample of M giants at Baade's window. The determination of abundances for M giants developed by Terndrup et al. (1991) looks very promising in this respect.

The number of M giants for which we obtained velocities is small in the fields F588, F589 and M22, because the color and magnitude selection cuts were designed to include K giants. However, comparison of the kinematics of the M giants with the kinematics of the halo and bulge shown in figures 1 and 2 reveals that the M giants clearly can be associated with the bulge rather than the halo. Unfortunately, we cannot determine abundances for these objects, to

see if the more metal rich ones follow show the same kinematics as the Miras, of which they are progenitors. The magnitude and color selection applied to our samples imply that we are not including the cooler, more metal rich giants.

Sharpless et al. (1990) argue that these M giants in Baade's window are 3–5 Gyr old, on the assumption that they have $[\text{Fe}/\text{H}] \sim +0.5$. However, the abundance they adopt is too high: Smith & Plez (1993) find a mean metallicity $[\text{Fe}/\text{H}] = 0.0$, with a range from -0.2 to $+0.2$, from echelle spectra and model atmospheres. Then, the M giants are probably older.

7.4. Other Tracers of the Bulge and Halo

Here we will discuss the comparison of the present results with other published kinematics of the bulge from different tracers. Given that there is a metallicity gradient in the bulge, and that the halo is present in the bulge fields, we will try to associate different tracers with different components. This will tell us how our observations fit into the current knowledge of the populations in the inner Galaxy.

Table 1 presents all the published radial velocity and proper motion measurements in bulge fields. The first column identifies the objects observed. Column 2 gives the field name, or the range in latitudes and longitudes covered. Column 3 gives the rate of increase of the mean line of sight velocity per degree away from the minor axis. Columns 4, 5 and 6 give the velocity dispersion, its associated error, and the total number of objects used to compute this. Column 7 gives the metallicity of the different samples. Finally, column 8 lists the references.

Table 7.1: PUBLISHED VELOCITIES

OBJECTS	Field	$\langle V \rangle / \text{deg}$	σ	Err	N	[Fe/H]	Reference
Integ light	Sgr1	..	122	7	..	all	Freeman + 1988
M5-9 giants	BW	..	113	11	49	>-0.5	Mould 1983
M5-9 giants	BW	..	113	6	225	>-0.5	Sharples + 1990
M giants	b=-3	..	116	..	..	..	Terndrup 1993*
M giants	b=-10	..	67	..	..	..	Terndrup 1993*
K giants	BW	..	104	12	53	all	Rich 1990
K giants	-10,-10	8	67	6	..	>-1.0	Morrison + 1993
K giants	-10,-10	4	107	6	..	>-1.0	Morrison + 1993
TO stars	10,-22	2	103	12	41	all	Harding 1990
TO stars	-15,-14	3	83	10	43	all	Harding 1990
Miras	|1|<20	..	122	15	34	>-0.5	Feast + 1987
Miras	|1|<20	10	76	10	29	>-0.5	Menzies 1992
Miras	|1|<20	11	90	12	25	>-0.5	Catchpole 1992
PN	|1|<10	14	103	6	147	..	Kinman + 1988
RR Lyraes	BW	..	133	25	17	<-0.8	Gratton 1987
RR Lyraes	b=8,-8	..	62	10	18	<-0.8	Rodgers 1977
RR Lyraes	BW	..	127	15	36	<-0.8	Tyson 1991
OH/IR	-7<l<10	10	70	..	..	mr	Nakada + 1993
OH/IR	-5<l<10	10	110	..	..	mr	Dejonghe 1993**
C stars	-3<b<-11	..	113	14	31	?	Tyson + 1991

Notes to table 1:

* Unpublished values quoted by Kent (1992)

** Value quoted by DeZeeuw (1993)

7.4.1. The RR Lyraes

Baade (1951) discovered RR Lyraes in Baade's window, and that led him to propose that the bulge population was similar to that of the globular clusters. The population associated with the RR Lyraes we see towards the bulge is similar to the globular clusters. The bulk of the bulge population, however, is not, as demonstrated by the findings of Nassau & Blanco (1964) and of Whitford (1978), later confirmed by the abundances of K giants determined by Whitford & Rich (1984).

The RR Lyraes at Baade's window are metal poor (Walker & Terndrup 1991), and have a high velocity dispersion (Gratton 1988, Tyson 1991). They are then considered here to be halo members. The only other published kinematic study of RR Lyraes in bulge fields that we are aware of is that of Rodgers (1987). He measured distances and radial velocities for 18 variables in the Oort-Plaut fields, at $l, b = (0, 8)$, and $(0, -8)$. He finds $\sigma_{RRLyr} = 62 \pm 10 \text{ km s}^{-1}$, and a mean velocity of $V_m = -40 \pm 15$. This is not in conflict with our arguments, since most of the RR Lyraes observed by Rodgers (1987) are associated with the disk, according to Rodgers (1991). Taam, Kraft & Suntzeff (1976), and more recently Layden (1993) find that there is a population of RR Lyraes with thick disk kinematics at intermediate heights above the plane. The kinematics and distances of Rodgers (1987) sample would place them in the thick disk population (Rodgers 1991). This is an important point, the other possibility is that these RR Lyraes are mostly bulge members, that just happened to have low σ because of the dependence of σ_{bulge} with distance from the Galactic center, as argued by

Rich (1993), also Tyson & Rich (1991). However, Rodgers (1991) proved that the RR Lyraes of his sample are not bulge RR Lyraes, but belong to the thick disk. It is interesting to note that Oort & Plaut (1975) find that the RR Lyraes of high and low metallicity show practically identical density distributions in the inner Galaxy. Oort & Plaut (1975) also noted that the expected velocity dispersion of the bulge RR Lyraes is very similar to the observed velocity dispersion of metal poor RR lyraes in the Solar neighborhood.

We argue therefore that the RR Lyraes found in the bulge windows represent the inner halo, and that their kinematics and metal abundances are different from the bulge giants. We expect no similar dominance of bulge RR Lyraes, since at high metallicity they are probably all RHB stars. As discussed in chapter 4, Suntzeff et al. (1992) estimate that the rate of production of RR Lyraes is 50 times larger for the metal poor halo globulars than for the metal rich globulars. The K giant counterpart for that inner halo population is small compared to the bulk of the bulge giants that so far they have not been separated. The first attempts are done here and also in an outer bulge field by Morrison & Harding (1993).

7.4.2. The Bulge Carbon Stars

The bulge is deficient in C stars (e.g. Blanco 1965, Blanco 1986). This is an important observation, because the absence of luminous C stars implies that the bulge did not form by late merging of LMC-type satellites (Rich 1990).

The C/M star ratio of the bulge is much different from the disk and from the Magellanic clouds (e.g. Blanco 1988). This difference with the Magellanic

Clouds can be attributed to the Clouds being more metal poor or younger, either of which is conducive to occurrence of C stars. But the local disk is metal rich, with about the same mean metallicity as the bulge (McWilliam & Rich 1993). In consequence, the argument of the metallicity does not work to explain the absence of C stars in the bulge. There are two alternative explanations: the bulge is much older than the local disk and the Clouds, and/or the bulge chemical evolution is much different. We argue that both reasons are correct.

It would be interesting to ask if a rapid formation scenario for the bulge (e.g. ELS) produces a $[C/O]$ ratio much smaller than Solar. There are indications that this is possible from the detailed models of chemical evolution of Matteucci (1993). The ratio $[C/O]$, and not $[Fe/H]$, is going to be the driver for the presence of C stars. This is important point: it means that for two populations with the same metallicity, one formed rapidly, and the other formed slowly, the latter will have C stars, while the former will not.

Recently, Azzopardi, Lequeux & Rebeiro (1985) discovered a handful of under-luminous C stars in bulge windows. These 33 bulge C stars are studied by Tyson & Rich (1991), and show contradictory kinematics. On one hand, their velocity dispersion drops with increasing latitude, as expected if they were bulge members. On the other hand, the velocity dispersion in the inner fields is too high, consistent with halo membership. Given the small size of their sample, it is difficult to associate these faint C stars with either the bulge or the halo at this point. Unfortunately, the evolutionary status of these faint bulge C stars is not clear, neither is their origin (Azzopardi, Lequeux, & Rebeiro 1988, 1993, Tyson & Rich 1991)

7.4.3. The Planetary Nebulae

The kinematics of the planetary nebulae in the Galactic disk and halo are studied by Maciel & Dutra (1992). They find that the planetary nebulae in the disk share the disk rotation, and have small velocity dispersions $\sigma = 16.5 \text{ km s}^{-1}$, confirming the early results of Oort (1965). On the other hand, the relatively few planetary nebulae located at large distances from the Galactic plane ($\langle Z \rangle = 7 \text{ kpc}$) have halo kinematics: $\sigma_z = 83 \text{ km s}^{-1}$.

The kinematics of the planetary nebulae towards the Galactic bulge are discussed by Kinman et al. (1989). They find that the mean velocity increases away from the minor axis as $V_m = 12.0 l - 13.6 \text{ km s}^{-1} \text{ deg}^{-1}$, and a mean velocity dispersion $\sigma = 103 \text{ km s}^{-1}$. The masses of these PN are consistent with old progenitors (Kinman et al. 1989).

Acker et al. (1991) report an extensive study of PN in progress. Their preliminary results indicates that the mean velocity increases $15 \text{ km s}^{-1} \text{ deg}^{-1}$ with distance from the Galactic center. Their kinematics are also consistent with metal rich bulge stars, and with the results of Kinman et al. (1989).

The maps of Pottasch (1992) illustrate very clearly that there are numerous PN associated with the bulge itself. There are many PN also associated with the inner disk, but a judicious latitude selection will account for them.

In conclusion, the PN trace the kinematics of the metal rich bulge. Of all the other bulge tracers, perhaps the PN are the most important ones, in the sense that they are easily observable, providing excellent radial velocities, distances and abundances. The study of the large sample of bulge PN observed

by IRAS will be a nice complement for the bulge kinematics. They would also give an excellent reference point for the study of distant ellipticals and bulges of spirals.

7.4.4. The OH/IR Stars

The concentration of IRAS sources is discussed by Frogel (1988), Harnon & Gilmore (1988), Habing et al. (1985), and Van der Veen & Habing (1990). In general, these evolved stars are more concentrated than the V light or the K giants. These observations determined that the size of the bulge is $-10^\circ \leq b \leq 10^\circ$, and $-15^\circ \leq l \leq 15^\circ$.

Van der Veen & Habing (1990) study a sample of OH/IR stars in the Galactic bulge, representative in general of the much larger sample of similar stars that IRAS detected. They argue that these stars are evolved from the Miras found in bulge windows. They also analyze the luminosity function to conclude that the Miras and OH/IR stars have low mass progenitors ($1.0\text{--}1.4 M_\odot$), and are therefore 7–15 Gyr old, contrary to the much younger ages inferred by Harmon & Gilmore (1988). This range of ages is confirmed by Whitelock & Catchpole (1991), who argue that there is no reason to propose an intermediate age Mira population in the bulge, on the basis of their periods. Of course, the problem of deriving masses (and therefore ages) for Miras is that the bulge Miras are probably metal rich, like the underlying population. However, there is no hard evidence to suggest that the Miras are young (e.g. Renzini 1992, Whitelock 1993).

Lindqvist, Habing & Winnberg (1992) find that the OH/IR stars close to the Galactic center can be divided into 2 groups. The first one is associated with the disk, the other one contains older stars, with higher velocity dispersions.

Comparing the distribution of IRAS Planetary Nebulae given by Pottasch (1992) with the IRAS maps of the OH/IR stars of Habing (1988, 1993), we see that the latter are slightly more flattened and concentrated to the Galactic plane. Pottasch (1992) argues that the PN and the OH/IR stars are associated.

The population of OH/IR stars is clearly composite, including members of the disk and of the bulge. The halo is probably not represented. The bulge OH/IR stars are mostly (but not only) associated with the most metal rich bulge giants, according to the kinematics.

7.4.5. Miras and Other Long Period Variables

Catchpole (1991) and Menzies (1991) measured a handful of radial velocities for long period variables in the direction of the Galactic bulge. Menzies (1990) finds $V_{rot} = 10 \pm 1 \text{ km s}^{-1}$, and $\sigma = 76 \text{ km/s}$, from 29 IRAS-selected variables in the vicinity of the bulge. Catchpole (1990) finds $V_{rot} = 13 \pm 1 \text{ km s}^{-1}$, and an overall $\sigma = 90 \text{ km/s}$, from 25 confirmed Mira variables in the bulge.

It is clear from the kinematics that most of these Miras belong to the bulge rather than the halo, though a few can be disk members. The disk Miras should be minority due to the latitude selection used (the IRAS observations show a lot of confusion close to the Galactic plane, these Miras are typically at more than 5 degrees from the plane). The distances are also consistent with bulge

membership (e.g. Whitelock 1991). The kinematics of these Miras imply that they are associated with the high metallicity bulge giants, with higher rotation and smaller velocity dispersion than the more metal poor bulge giants. This is important, because it could be argued that some of the short period Miras (older) are halo objects, and only longer period Miras (younger) are associated with the bulge itself (c.f. Rich 1993), therefore inferring that the bulge is young. However, the kinematics put them among the bulge population. Instead, we would argue that some of the long period Miras (younger) are associated with the disk, and the bulk of them are an older, bulge population, with virtually none associated with the halo (c.f. also Whitelock et al. 1992). We recall that most of the Miras found in globular clusters appear in metal rich globulars, which we associate with the bulge –section 9–, and not in metal poor, halo clusters (e.g. Feast 1987). By analogy, none of the Miras in the bulge fields are expected to belong to the halo.

Glass (1993) finds that the bulge Miras cut off at $M_{bol} = -5.5$, and thus are no more luminous than the OH/IR stars. The kinematics of these 2 different bulge tracers are also very similar, and follow the most metal rich K giants of the present study.

Whitelock (1992) studied the spatial distribution of the bulge Miras, arguing for an extended distribution along the line of sight, consistent with the presence of a bar in the inner kpcs.

7.5. Chemical Evolution of the Bulge

We have discussed the kinematics, stellar populations, compositions, and spatial distribution of the bulge. The only other important piece of evidence not yet included is the detailed chemical evolution of the bulge, mostly because we do not have sufficient data on this. However, here we will briefly summarize what is known about the chemical evolution of the bulge.

Along the lines of Wyse & Gilmore (1992), we will now speculate about what to expect in terms of bulge chemical evolution from the results of this dissertation. The ejecta from massive stars that undergo SN type II explosions are rich in oxygen, α elements (Mg, Si, Ca, Ti), and r -process elements with respect to elements of the iron peak (Fe, Cr, Mn, Sc, V, etc); On the other hand, the explosions from SN type I produce more heavy elements with respect to light elements (e.g. Arnett 1978, Wyse & Gilmore 1992, Spite & Spite 1985, Hashimoto et al. 1989, Wheeler, Sneden & Truran 1989, Nomoto et al. 1989, 1992, Thielemann, Nomoto & Fujimoto 1990, Arnett 1992).

We argue that the bulge formed from leftover halo gas. The halo stars have oxygen and α elements enhanced with respect to iron due to enrichment by SN type II only (e.g. Wheeler, Sneden & Truran 1990, Minniti et al. 1993). Since the formation of the halo was slow and chaotic, the bulge gas had the opportunity to be enriched by the ejecta from SN type I, resulting in gas compositions with $[O/Fe]$ and $[\alpha/Fe] \sim 0$. If the bulge star formation took place rapidly (e.g. Matteucci & Brocato 1991), then bulge SN type II would have been important in driving the O and α element abundance up again. We would then expect $[O/Fe]$ and $[\alpha/Fe] \geq 0$, consistent with the results of McWilliam & Rich (1993,

also Barbuy & Grenon 1992). However, if the formation of the bulge was slow, the iron peak elements would dominate ($[O/Fe]$ and $[\alpha/Fe] \leq 0$), contrary to the observations.

The real test, however, will be given by the measurement of detailed abundances for large numbers of giants spanning the whole abundance range found in bulge fields. The available data (McWilliam & Rich 1993, Edvarsson et al. 1993), suggest that the chemical evolution of the bulge is also different from that of the local disk. In particular, at a given $[Fe/H]$, the bulge giants have higher $[Al/Fe]$, $[Mg/Fe]$ and $[Ti/Fe]$ than the disk giants. The presence of enhanced Eu abundance also suggests the SN type II played an important role in the enrichment of the bulge, unlike the disk. The metal rich globular cluster M71 and the bulge giants seem to share similar detailed chemical composition, suggesting similar chemical evolution (Snedden et al. 1993).

7.6. The Metallicity Gradient

Here we will review the evidence for a metallicity gradient of the bulge, which is a crucial piece of evidence in favor of formation via dissipational collapse.

There is a well known metallicity gradient in the bulge fields, as shown first by Terndrup (1988). The presence of a gradient is clear, as reviewed by Terndrup (1993), although not all the determinations agree with each other in the extent or even scale of the metallicity gradient. Note that Terndrup (1993) does not consider the flattening of the bulge when comparing all the different metallicity determinations. This is important to take into account when comparing fields along the minor axis with off-axis fields.

Table 7.2 : METALLICITY DETERMINATIONS IN BULGE FIELDS

Field	l, b	<[Fe/H]>	r*	Method	Reference
BW	1, -4	0.0	0.56	VI	Terndrup 1988
6deg	0, -6	-0.2	0.84	BVI	Terndrup 1988
8deg	0, -8	-0.4	1.11	BVI	Terndrup 1988
10deg	0, -10	-0.7	1.39	BVI	Terndrup 1988
BW	1, -4	0.20	0.56	CMT1T2	Geisler & Friel 1992
MH	-10, -10	-0.8	1.69	CMT1T2	Morrison & Harding 1993
Sgr3	0, -3	0.10	0.42	CMT1T2	Tyson (1991, 1993)
BW	1, -4	0.39	0.56	CMT1T2	Tyson (1991, 1993)
6deg	0, -6	0.74	0.84	CMT1T2	Tyson (1991, 1993)
8deg	0, -8	0.07	1.11	CMT1T2	Tyson (1991, 1993)
10deg	0, -10	0.20	1.39	CMT1T2	Tyson (1991, 1993)
13deg	0, -13	-0.62	1.80	CMT1T2	Tyson (1991, 1993)
17deg	0, -17	-1.07	2.38	CMT1T2	Tyson (1991, 1993)
BW	1, -4	0.3	0.56	Spectra	Rich 1988
BW	1, -4	-0.25	0.56	Spectra	McWilliam & Rich 1993
BW	1, -4	0.0	0.56	Spectra	Smith & Plez 1993 **
F588	8, 7	-0.6	1.25	Spectra	This dissertation
M22	10, -7	>-0.6	1.43	Spectra	This dissertation

* : equivalent distances in kpc along the minor axis for a flattened bulge ($c/a = 0.7$)

** : M giants only

Table 2 presents all the determinations of the metal abundance in bulge fields. Essentially, four techniques have been used: BVI photometry (Cook 1987, Terndrup 1988), JHK photometry (Frogel et al. 1991), Washington photometry (Geisler & Friel 1992, Tyson 1991, Morrison & Harding 1993), and spectroscopy (Rich 1988, McWilliam & Rich 1993, Smith & Plez 1993, this dissertation). These results are all plotted in figure 4.

The most reliable of these techniques is spectroscopy. However, note that Rich (1988) finds a mean metallicity at BW of $[\text{Fe}/\text{H}] = +0.3$ from low dispersion spectra, while the high dispersion echelle spectra analyzed with model atmospheres and spectral synthesis techniques give a mean metallicity $[\text{Fe}/\text{H}] = -0.25$ for BW (McWilliam & Rich 1993). This new more metal poor scale is also supported by high dispersion spectroscopy of M giants in BW (Smith & Plez 1993). We have obtained metallicities of K giants based on medium dispersion spectra, calibrated solely on the scale of the globular clusters. Although the highest metallicity bins are not well defined, the mean abundance in field F588 is $[\text{Fe}/\text{H}] = -0.55$. This is the mean abundance of bulge + halo + disk giants present in the field, which is dominated by bulge giants. The same is the case for BW. Field F589 is complicated by the presence of substantial numbers of disk giants, therefore it does not give any useful metallicity information. The M22 field is affected by selection effects, as discussed in chapter 5, that work against the inclusion of metal rich bulge giants. Therefore, it only gives a lower limit for the mean metallicity, $[\text{Fe}/\text{H}] \geq -0.60$. If we refer the F588 and M22 fields to the minor axis, taking into account the flattening of the bulge $\epsilon = 0.3$, they would

Figure 7.4 Mean metallicities published for bulge fields. Open squares are from Terndrup (1988) BVI photometry. Stars are Washington photometry of Tyson (1993), Geisler & Friel (1992) and Morrison & Harding (1993). Filled triangles are spectroscopic determinations from Rich (1988), McWilliam & Rich (1993) and this work.

correspond to $b = 10$ and 12 degrees, respectively. Thus, from spectroscopy we find a gradient $d[Fe/H]/dr = 0.05 \text{ dex kpc}^{-1}$ along the minor axis.

However, the question still open is whether this gradient is real or merely due to a population transition (different relative contributions of bulge and halo stars with distance from the center). Discounting the stars with $[Fe/H] \leq -1$ at BW, that are mostly halo giants on kinematic grounds, we find a mean metallicity for the bulge itself of $[Fe/H] = -0.1$ at BW from the data of McWilliam & Rich (1993). Discounting the halo giants in our fields F588 and M22 we find mean metallicities $[Fe/H] = -0.3$ and ≥ -0.3 , respectively. In consequence, the gradient in the bulge itself is somewhat shallower, but still present: $d[Fe/H]/dr = 0.03 \text{ dex kpc}^{-1}$ along the minor axis. If we use the old Rich (1988) scale, the metallicity gradient in the bulge itself would be $d[Fe/H]/dr = 0.10 \text{ dex kpc}^{-1}$. Clearly, more work is needed on this particular issue, because the absolute spectroscopic abundance scales are not very well defined yet.

Unfortunately, the situation is not better for the photometric metallicities. Terndrup (1988) from the color of the bulge red giant branch in optical bands inferred a gradient $d[Fe/H]/dr = 0.12 \text{ dex kpc}^{-1}$. This was not confirmed by the near-IR photometry of Frogel et al. (1990), who find no variation in color for the M giants along the minor axis: $d[Fe/H]/dr \approx 0 \text{ dex kpc}^{-1}$. However, the spectroscopy of Terndrup et al. (1990) confirms that the TiO bands are stronger in M giants closer to the Galactic center, finding $d[Fe/H]/dr \approx 0.05 \text{ dex kpc}^{-1}$. Furthermore, the near-IR photometry presented in chapter 3 reveals clearly a

gradient, with $d[Fe/H]/dr \approx 0.1 \text{ dex kpc}^{-1}$, confirming the results of Terndrup (1988). We note that this IR photometry is based on the mean location of the bulge RGB using globular clusters as reference. Therefore, it considers the whole K + M giant population, not only the M giants like Frogel et al. (1990).

The Washington photometric system (defined by Canterna 1976) was used by Geisler & Friel (1992), Tyson (1991), and Morrison & Harding (1993) to derive abundances of bulge giants in different fields. They all obtained metallicities using the calibration of Geisler, Claria & Minniti (1991), so their relative abundances should be on the same system. However, there are many difficulties for the photometry in these crowded bulge fields. Tyson (1991) and Geisler & Friel (1992) obtain the same mean metallicity for Baade's window, which is about 0.5 dex higher than the mean metallicity derived by McWilliam & Rich (1993). The field of Morrison & Harding (1993) at $l, b = (-10, -10)$ would lie at a projected latitude $b \approx 13$ degrees accounting for the flattening of the bulge. They find a mean metallicity $[Fe/H] = -0.8$. A very steep gradient in metallicity $d[Fe/H]/dr = 0.18 \text{ dex kpc}^{-1}$ results from these observations.

However, Tyson (1991) scaled his metallicities upward to agree with the abundances of Rich (1988) in Baade's window. Otherwise, he would have obtained the same abundances as McWilliam & Rich (1993) in the BW field. In this latter –more accurate– scale the photometry of Tyson (1991) predicts $[Fe/H] \approx -1.35$ at $b = 13$, which differs by 0.5 dex from the mean abundances of Morrison & Harding (1993).

Tyson (1993, see also Rich 1993) argue that the mean metallicity is constant within 1 kpc from the Galactic center, unlike the results of Terndrup (1988).

If true, this is important because it would suggest a dissipationless collapse formation for the bulge, contrary to the kinematic arguments. However, the proof that $[\text{Fe}/\text{H}]$ decreases away from the center is clearly seen by comparing the color-magnitude diagrams of Udalski et al. (1993) at BW (at 0.5 kpc) with the field at -8 degrees (at 1 kpc), or the color magnitude diagrams of Ortolani & Rich (1993, shown by Renzini 1993) at BW with the -8 degree field, and the SgrI field (shown by Rich 1993).

To summarize, the abundances determined from photometry in bulge fields are not accurate, although the presence of a radial gradient seems well established for the whole population bulge plus halo and disk.

7.7. The Role of the Globular Clusters in the Inner Galaxy

7.7.1. Introduction

In this section we discuss the insertion of metal-rich globular clusters near the Galactic center into the component populations of the Galaxy, namely the thick disk and bulge. It is concluded that the majority of the inner metal rich globulars are associated with the bulge rather than the thick disk. This conclusion is based on the spatial distribution, kinematics, age, and metal abundance.

This discussion of the disk globular clusters is based on the papers by Frenk & White (1980, 1982), Zinn (1985), Armandroff (1989), and Zinn (1990, 1993). Two new results on the Galactic bulge are relevant to the discussion: 1) McWilliam & Rich (1993) revise the mean metallicity of the bulge by ~ -0.5

dex; and 2) Minniti et al. (1992) and this dissertation unveil the kinematics of the Galactic bulge as function of metallicity. The addition of a few clusters for which we have obtained new radial velocities, distances and metallicities do not change the results.

Zinn (1985) divided the globular clusters into halo and disk subsystems, according to their metal abundances, and showed that the halo globulars have metallicities, distribution and kinematics that resemble the Galactic halo. In contrast, the metal-rich globulars form a much more flattened, kinematically cold, disk-like system. Armandroff (1989) used an improved database (with the addition of new radial velocities and metallicities from Armandroff & Zinn 1989 and distances from Armandroff 1988), to confirm and strengthen the results of Zinn (1985). In particular, Armandroff (1989) made the case for the metal-rich globulars to be associated with the thick disk, based mostly on the kinematic similarities. However, these fundamental papers were confined to the use of globulars with $R \geq 3$ kpc, for very good reasons (the inner clusters have uncertain distances, inaccurate metallicity determinations, lack of color-magnitude diagrams, etc). Here we will discuss the role of the inner metal rich globulars, and their relationship to other Galactic components based on the spatial distribution, metallicity, kinematics, stellar content and ages.

There are several stellar component populations of our Galaxy, which may or may not be distinct: the halo, the bulge, and the thin and thick disk. Except for the bulge, all the other Galactic components have clusters associated with them. The thin disk has open clusters, the halo has the halo globulars, and the

thick disk has the disk globulars. Why did Zinn (1985) or Armandroff (1989) not consider the bulge as the host population for some of these clusters? The main reason is that at the time of their investigations, the kinematics and stellar populations of the bulge were not very well understood.

7.7.2. The Spatial Distribution

The distribution of known metal-rich globular clusters is very concentrated to the Galactic center (Frenk & White 1982). From the metal rich cluster sample of Armandroff (1989), we see that all are inside the Solar circle, and the majority of them lie within 5 kpc of the Galactic center. This is true even without considering selection effects; the metal rich cluster sample is biased towards clusters outside the bulge.

Looking at the distribution of the metal-rich globulars projected onto the sky, as given for example by figure 5 of Thomas (1989), we see that only 12 clusters are outside of 30 degrees from the Galactic center (Pal3 is not included because it is metal poor), while 38 clusters are inside of 30 degrees. Furthermore, the median radius is 11.5 degrees, or 1.7 kpc projected distance. This is indeed a surprising number, since most of the missing globulars are expected to lie in the inner kiloparsec, implying that 11.5 degrees is only an upper limit to the median radius, a value ≤ 10 degrees is more likely. For an exponential thick disks with radial scale-length $H_r = 4$ kpc, the median radius is much larger. Most of the known globulars without measured metallicities are concentrated towards the Galactic center and Galactic plane. Figure 1 of Armandroff (1993)

nicely illustrates that 2/3 of the globulars without abundances lie within 20° of the Galactic center.

It is true that the metal-rich globulars do not appear to be as concentrated as the integrated light of the bulge. However, there are 2 important facts to consider, that would contribute to such an effect: 1) there are some missing globulars in the inner Galaxy, and 2) the dynamical destruction processes would be stronger closer to the Galactic center. The number of missing clusters is very hard to estimate, Zinn (1990) argues that ≥ 30 clusters are missing, while Racine & Harris (1989) estimate that ≤ 10 clusters are missing. All the destruction processes are enhanced in the inner regions, and the number of globulars we see today could have no resemblance to the primordial number (e.g. Aguilar et al. 1988).

Perhaps a more precise argument is given by the relative numbers of metal poor vs metal-rich globulars in the inner regions of the Galaxy. For example, from Zinn (1990, his figure 4) we compute the number ratio of metal rich vs metal poor globulars as function of angular distance from the Galactic center. The results are shown in figure 5, including the region outside $\omega = 15$ degrees as a single bin, where the relative metal rich to metal poor globular ratio is 0.16 (Zinn 1990). Figure 5 shows the steep increase in the number of metal-rich globulars towards the Galactic center. If we identify the metal poor globulars with the halo (Zinn 1985), then the distribution of metal rich globulars is much more concentrated than the halo. The only stellar population for which that is also true is the bulge. Note that the halo follows a density law of the form

Figure 7.5 Relative numbers of metal rich to metal poor globular clusters as function of projected angular distance from the Galactic center. This figure illustrates how much more concentrated are the metal rich globulars than the metal poor ones. This is consistent with the field populations in the inner 3 kpc, where the bulge giants are much more concentrated than the disk giants.

$r^{-3.2}$, as revealed by the halo globular clusters, the RR Lyraes, and the field blue horizontal branch stars (Zinn 1985, Saha 1985, Preston et al. 1992). Instead, the bulge stellar population follows a steeper power law (Terndrup 1988, Blanco & Terndrup 1989). The relative increase of the $r^{-3.2}$ density law is always faster than an exponential representing the thick disk towards the center. Recently, Morrison (1993) finds a thick disk to halo normalization of 52/1 in the Solar neighborhood. Using this normalization (which is larger than any previous estimate), we cannot find any exponential disk that would produce the effect seen in figure 5.

7.7.3. The Kinematics

The kinematics were one of the strong points that Zinn (1985) used to define the 2 populations of globular clusters. The *global* kinematics of the halo clusters is very similar to the *local* kinematics of the halo field stars. This is not mere coincidence, but due to the fact that the halo kinematics do not change much with Galactocentric distance, as seen earlier in this chapter. We do not know if this is the case for the thick disk. It is very possible that the *local* thick disk kinematics are not representative of the *global* kinematics of this component. In particular, the thick disk velocity dispersion could increase substantially towards the Galactic center, as does the σ of the old thin disk (Lewis & Freeman 1989).

Armandroff (1989, 1993) used the kinematic arguments to associate the thick disk with the metal-rich globulars *outside* of 3 kpc from the Galactic center. The metal-rich globulars seem to be rotating more rapidly than the

bulge, as does the thick disk ($V_{rot} = 177 \pm 25$ and $\sigma = 58 \pm 11$ for the metal-rich globulars, vs $V_{rot} = 110 \pm 15$, and $\sigma = 70 \pm 20$ for the bulge giants). At the same time, the spatial distribution of the metal-rich globulars is flattened. However, the kinematics or spatial distribution of the thick disk stars as function of Galactocentric distance are not known.

Frenk & White (1980) developed a method for treating the kinematics of the globular cluster system with the assumption of constant velocity. If we consider the clusters close to the Galactic center, the constant rotational velocity solution is problematic, because of the distance errors (Armandroff 1993, Zinn 1990). However, the line of sight velocity dispersion of the disk globulars is not affected by distance errors. Zinn (1990) gives $\sigma = 77 \pm 14$ km/s for the disk globulars within 15 degrees (or 2.1 kpc) of the Galactic center. This is very similar to the velocity dispersion of the metal rich bulge giants. For the metal poor globulars in the same region, Zinn (1990) gives $\sigma = 126 \pm 20$ km/s, very similar to the values we find for the metal poor (halo) giants in the direction of the bulge. He also points out that there is no evidence for a more rapid rotation of the metal rich group, which is possibly due to the uncertainties in the distances.

The distances to the clusters with $R_{Gal} \leq 3$ kpc are a big problem. This was discussed by Frenk & White (1982), and it is well illustrated by Thomas (1989), who plots the projected distribution of the globular clusters in different planes. His figures 5 show a very clear "finger of God" effect in the plane of the Galaxy. The distance problem cannot be stressed enough: to study the distribution of clusters one should use the projected distribution in the sky,

and *not* the distances available in the different compilations. For example, van den Bergh (1993) computes the median radius of the metal rich clusters with $[\text{Fe}/\text{H}] \geq -1.0$ to be $R_h \approx 4$ kpc (for $R_0 = 8.5$ kpc) using distances. This is an overestimate. The value of $R_h \leq 1.7$ kpc is more realistic (we used only clusters with $[\text{Fe}/\text{H}] \geq -0.8$ to be consistent with Zinn 1985 and Armandroff 1989). Thus, van den Bergh (1993) recognized that the metal rich clusters form a concentrated population, confirming the results of Frenk & White (1982), but he does not associate them with the bulge.

Assuming a common distance for the clusters within 20 degrees from the Galactic center (more than 2/3 of the metal-rich globular cluster population), results in distance errors of the order of 10–30%. Clearly, this is much better than considering the distances compiled by Webbink (1985) which may have large errors (Armandroff 1989), and much better than rejecting the majority of the clusters. The distances adopted by Armandroff (1989) are of higher quality, and the "finger of God" effect is not so pronounced. However, one always worries about the division between "good" clusters and "bad" clusters. For example, "good" clusters for the kinematics are preferentially those far away from the Galactic center. These are the minority, and could not be representative of the whole metal rich population. Thus, in this particular case, the division between "good" and "bad" clusters reduces substantially the sample size, with the central clusters systematically underrepresented.

Furthermore, the bulge is better described by a solid body rotation model than by constant rotation. If the inner metal rich globulars are associated with

the bulge, a solid body rotation should be fitted to these clusters. Figure 6 shows the velocities for the metal rich clusters within 30 degrees of the Galactic center, along with the bulge rotation found in this dissertation. The data for this figure were taken from Zinn (1985) and Armandroff & Zinn (1988). There are no significant differences between the two systems.

In summary, the kinematics of the metal-rich globulars are consistent with membership in a thick disk population outside of 3 kpc. Inside of that region, the metal rich globulars have kinematics also consistent with membership in the bulge population. The inner metal poor clusters have halo kinematics outside and inside of 3 kpc.

7.7.4. The Ages

If the inside-out picture of Galaxy formation is correct, we can expect to find the oldest stars in central kpc of the Galaxy (e.g. Lee 1992, Zinn 1993). But in view of the differences in kinematic and metallicity between true halo and bulge stars found here, a difference in age is also likely. Then, we can conclude that these oldest Galactic objects belong to the inner halo, which formed first in the inside-out picture. The bulk of the bulge population could be younger than them. It is not clear how young the bulge is, due mostly to uncertainties in reddening, distance and the metallicity spread. Terndrup (1989) finds an age of 10–13 Gyr, while Baum et al. (1993) and Holtzman et al. (1993) argue for an age of less than 10 Gyr.

One must keep in mind that the formation of the halo possibly lasted 3–5 Gyr, a significant fraction of the Hubble time. When did the bulge form? Since

Figure 7.6 Velocities for the metal rich clusters within 30 degrees of the Galactic center, along with the bulge rotation found in this dissertation (solid line). Note that the solid line is not a fit to the clusters.

this is such a large range, it is possible that the bulge overlaps in age with part of the halo population. If the disk globular cluster system is to be associated with the bulge rather than the thick disk, then the bulk of the bulge population has an age of 10-13 Gyr. These are ages of NGC 6553 determined by Ortolani et al. (1991), and by Demarque & Lee (1992), and of 47 Tuc and M71 by McClure et al. (1987), Hodder et al. (1992).

The most visually compelling evidence to associate the metal-rich globulars with the Galactic bulge is the similarity of the deep optical CMDs of both populations, as shown by Ortolani and collaborators (Ortolani et al. 1991, 1992, 1993). CMDs in the near-IR also show close resemblance between the bulge stars and the metal-rich globular cluster stars, as seen in chapter 3.

7.7.5. The Metal Abundances

As discussed in chapter 4, most of the stars in field F588 more metal poor than $[\text{Fe}/\text{H}] = -1$ are halo rather than bulge giants, based on a kinematical definition of these terms. The transition between bulge and halo giants occurs at about the same metallicity where Zinn (1985) and Armandroff (1989) divide the cluster population into metal rich and metal poor.

Gilmore and Wyse (1985) found that the thick disk had a mean abundance $\langle [\text{Fe}/\text{H}] \rangle = -0.6$ at the Solar distance. Further investigations confine the metal abundances of thick disk stars to the range $-1.6 \leq [\text{Fe}/\text{H}] \leq -0.3$ (e.g. Morrison, Flynn & Freeman 1990, Croswell et al. 1991, Norris & Green 1989, Edvarsson et al. 1993). Zinn (1985) points out that there are none or very few

metal poor disk globulars. This is contrary to what one would expect from the observations in galaxies other than our own, where the clusters are in general more metal poor than the stellar populations (see e.g. Zinn 1990).

On the other hand, the metal-rich globular clusters have roughly the same metallicities as the bulk of the bulge giants. A slightly different abundance distribution would not be surprising, given by analogy that the halo globulars and field stars have slightly different abundance distributions (e.g. Suntzeff 1993). More importantly, the range of abundances of the disk globulars overlaps that of the bulge giants, given that the tails of the bulge metallicity distribution are associated with the inner disk and halo. In particular, the mean metallicity of the bulge K giants is $[Fe/H] \sim -0.4$ dex, and the metallicity range can be taken to be $-1.0 \leq [Fe/H] \leq +0.5$, considering the radial abundance gradient in the bulge. The higher limit is not well determined. However, there is at least one globular, Ter1, that has a higher abundance than the bulge field population at Baade's window, as found by Ortolani et al. (1993). There are also a few other globular clusters that have higher than Solar metallicity (e. g. Pal6 –this dissertation–, Liller 1 –Armandroff 1989–, etc).

One of the main arguments used by Zinn (1990) to decide that the globular clusters are not associated with the bulge is shown in his figure 5 (reproduced here as our figure 7), where he argues that the mean abundances of bulge giants and globulars are very different. Perhaps comparing a subsample of the clusters

Figure 7.7 Metallicity *vs* angular distance from the Galactic center (a) and *vs* latitude (b), for all the clusters within 15° . This figure is equivalent to figure 5 of Zinn (1990), where we have plotted the metal rich clusters as solid circles. The line shows the mean abundances for bulge fields along the minor axis from Terndrup (1988), shifted to give $\langle [Fe/H] \rangle = -0.3$ at Baade's window (McWilliam & Rich 1993).

to the bulge is more appropriate, since the metal poor clusters seem to be halo objects. If one distinguishes the metal-rich from the metal-poor globulars, the difference between the metal-rich globulars and the bulge giants is not significant. Furthermore, the abundances obtained in the bulge fields are normalized to the mean metallicity of Baade's window, and the new echelle abundances by McWilliam & Rich (1993, see also Smith & Plez 1993)) shift the mean abundance at Baade's window to $[\text{Fe}/\text{H}] = -0.3$ dex. This is precisely the mean abundance of the metal-rich globulars in that region. Thus, on that new scale there is no apparent difference between the metallicities of the metal rich globulars and the bulge stellar population. Note also that the slopes of the metallicity gradients of both populations are similar.

Furthermore, the extensive near IR photometry presented in chapter 3 reveals that the mean color of the bulge giant branch is similar to the color of the metal-rich globulars, indicating that they have similar abundances.

Another important point raised by Norris & Green (1989, see also Sarajedini & Norris 1993) is the lack of red horizontal branch stars in the disk population, stars which are numerous in metal rich globulars. If we associate the metal rich globulars with the bulge, this apparent contradiction disappears.

7.7.6. The Formation History

Searle & Zinn (1978) proposed that the halo of the Galaxy formed first, with its globulars, by mergers of different protogalactic fragments. The oldest stars in the Galaxy are the halo stars in the inner kiloparsec, which represents the

biggest fragment situated logically in the center of the potential well, represented by the RR Lyraes. This is in partial agreement with the picture by Lee (1992). Afterwards came the bulge. It is younger than the halo, but it formed rapidly, in a dissipational collapse. At the same time the metal-rich globulars formed. Note that there is also evidence for a common nucleosynthetic history for the metal rich globulars and the bulge population (Snedden et al. 1993).

Note that Zinn (1993) concludes that the inner "old halo" clusters show the signature for dissipation – larger rotation velocity, smaller velocity dispersion, and increased flattening –, and that there is a smooth transition from these "old halo" to the "disk" globulars, suggesting that they are part of the same collapse. By analogy, it can be argued that the field halo stars and the bulge stars show the same dissipation signature, and that it would be natural to associate the globulars to the field stars of these respective components.

In our study of red giants in field F588, the only clear kinematic separation is found at $[\text{Fe}/\text{H}] \sim -1$. This may be interpreted as the separation between the halo and the bulge components. The velocity dispersions of these 2 populations of decisively different metallicities differ by more than 3σ , and their mean velocities differ by 2σ . This is very similar to what one finds for the globulars within $\omega = 20^\circ$.

7.7.7. Summary

The main conclusions of Zinn (1985) and Armandroff (1989) do not change: the globular clusters appear to form two separate subsystems. The difference

proposed here is that the metal-rich globulars are not associated mostly with the thick disk, but with the bulge. The reasons for this are clear similarities in chemical composition, kinematics, spatial distribution, and age.

Zinn (1990) concludes that the globular clusters within 3 kpc of the Galactic center are not representative of the bulge population because: 1) they are substantially more metal poor than the field stars, and 2) they have a more extended spatial distribution. We have demonstrated that with the new abundance scale for the bulge of McWilliam & Rich (1993), and with our IR photometry, the abundances of the metal rich clusters are similar to that of the bulge stellar population. We have also discussed that the spatial distribution of the metal rich clusters is more consistent with the bulge than with the thick disk.

The association of clusters to determined Galactic components goes deep into the heart of our whole knowledge of Galaxy formation and evolution. This is mostly because ages are most easily determined for clusters than for field stars. If the metal-rich globulars are associated with the bulge, an enormous progress for Galaxy formation will be made with the accurate determination of ages in a few metal-rich globulars.

7.8. The Formation of the Bulge

It is true that the existence of the Galactic thick disk is beyond reasonable doubt, and has to be explained. However, as Freeman (1989) noted, the thick disk is not necessary for pictures of spiral galaxy formation, because not all

galaxies have thick disks like the Milky Way. This was found by van der Kruit & Searle (1981, 1982, see also van der Kruit 1991). The existence of a thick disk in the Galaxy can be explained as a single isolated merger event (e.g. Statler 1988, Quinn, Hernquist & Fullager 1992). On the other hand, the existence of a halo, a thin disk and a bulge have to be explained by any Galaxy formation scenario. Surprisingly, the formation of the bulge and its fitting into the Galactic context have received relatively little attention.

The importance of knowing the formation history of the early Galactic components is that we can then have a clearer understanding of the cosmological universe. Obviously, if the bulge formed very rapidly (e.g. Matteucci & Brocato 1990), it should not be very young, otherwise the observable universe would be plagued with forming bulges, which we do not observe. On the other hand, if the bulge is the result of several accretion processes within the age of the Galaxy, we should observe a significant range in ages (and therefore carbon stars) in the bulge population. There is evidence for intermediate age stars in the bulges of nearby galaxies (as shown in M31 by Rich & Mould 1991, Rich, Mould & Graham 1993, and in M33 by Minniti et al. 1993), but they could represent just one or two single isolated events of accretion, and by no means the reason of formation for the bulk of the population in these systems. An intermediate age population is also seen in the vicinity of the Galactic center (e.g. Rieke 1993), but apparently is confined to the inner hundred parsecs, not extending into the main part of the bulge (Glass 1993). It is important to consider accretion events, because a significant part of the accreted satellite will end up in the inner regions

of the accreting galaxy (e.g. Hernquist 1989). Accretion of a stellar satellite is able to produce a thick disk, but what would happen when merging of several gas rich satellites (the Searle & Zinn scenario)?

Recently, Carney (1990) and Carney et al. (1990) pointed out a very simple but important fact: the gas leftover from the Galactic halo formation would have sunk to the bulge, rather than to the disk, due to its low angular momentum. It is well known that star formation is inefficient, only $\sim 10\%$ of the mass of the molecular clouds ends up in stars. The leftover gas has to go somewhere. It either sinks to the center of the gravitational potential due to its low angular momentum, or is blown away by supernovae winds. The second possibility is important in lower mass galaxies, but the Milky Way is massive enough that it should have retained a significant fraction of the gas. This was appreciated by Wyse & Gilmore (1992, 1993), who reviewed several possible alternatives for bulge formation. They preferred the idea that the halo formed first, preceding the bulge, based largely on Carney (1990). In this scenario there is a causal relation between the halo and bulge.

A contrasting scenario is presented by Lee (1992), who argues the opposite: the bulge formed before the halo, based on the evidence from RR Lyraes (see also Catelan & Freitas Pacheco 1993). However, Lee (1992) does not take into account the relation between the metal abundances and the kinematics of the bulge RR Lyraes, which are known (e.g. Gratton 1987, Tyson 1991). These kinematics, as shown above, determine that the RR Lyraes belong to a more kinematically hot system than the bulge population. That is, the majority of RR Lyraes in Baade's window belong to the halo, and not to the bulge.

It has also been suggested recently that bars in spiral galaxies have the ability to originate bulges by vertically heating disk stars in the inner regions. The resulting bulges would be boxy, built through resonant scattering by the bar of the stellar orbits (see the review by Kormendy 1993 and references therein). It is likely that this scenario would produce metallicity gradients in the inner bulges, and a dependence of kinematics on metallicity. These dependences should be checked in our Galaxy to test the scenario of bulge formation by secular heating by a bar. Open questions are, for example, if this would work for transient bars, since it is not clear how long bars last, or if they are even recurring phenomena.

Building bulges by secular evolution of the inner disk is an interesting idea, and can be tested observationally. One of the predictions of the mechanism is that the resulting box-shaped bulge rotate cylindrically. Observations of bulge giants carefully selected to remove contamination by other Galactic components at difference windows can be used to test that prediction.

The proposal that many bulges of late type spirals are merely disks (e.g. Kormendy 1993) is also based on the observation that many bulges of barred galaxies lie well above the oblate line in the $V/\sigma - \epsilon$ diagram. Our own Galaxy does not fit in this category: with $V/\sigma \sim 0.85$ (Minniti et al. 1992, deZeeuw 1993, Kent 1992), and $\epsilon = 1 - b/a \sim 0.35$ (Habing et al. 1985, Harmon & Gilmore 1988, Kent et al. 1991, Weiland et al. 1993), the Milky Way lies right on the oblate line.

If the bulge were an extension of the disk, we also have to explain why the tip of the bulge AGB observed by Frogel & Whitford (1987) is much fainter than the AGB tip of the local disk (e.g. Tinsley & Gunn 1976).

In the Milky Way, the halo could have formed first, with its globulars, by mergers of different protogalactic fragments (Searle & Zinn 1978). The oldest stars in the Galaxy are the halo stars in the inner kpc, which would have been the biggest fragment situated logically in the center of the potential well, represented by the RR Lyraes. This is in partial agreement with the picture by Lee (1992). Afterwards came the bulge, it is younger than the halo, but it formed rapidly, in a dissipational collapse fashion. At the same time the metal rich globulars formed. The thick disk formation is also not clear, could be a later accretion, or the intermediate step after the bulge and before the disk (e.g. Armandroff 1993, Wyse & Gilmore 1992, Quinn, Hernquist & Fullager 1992, Carney et al. 1990).

Note that Zinn (1993) concludes that the inner "old halo" clusters (those with $R_{Gal} \leq 6$ kpc, and blue horizontal branches) show the signature for dissipation – larger rotation velocity, smaller velocity dispersion, and increased flattening –, and that there is a smooth transition from these "old halo" to the "disk" globulars, suggesting that they are part of the same collapse. By analogy, it can be argued that the field halo stars and the bulge stars show the same dissipation signature, and that it would be natural to associate the globulars with the field stars of these respective components. This leads to one of the major conclusions of this dissertation: the halo material that collapsed fell into the bulge, rather than the disk, in agreement with the hypothesis of Carney et al. (1990).

We have argued that the metal poor stars in bulge fields belong to the halo, not to the bulge, on the basis of their metallicities and kinematics. This

is consistent with a younger age for the bulge, and with a causal connection between the formation of the halo and the bulge.

Not all bulges formed via late mergers, otherwise we should see many more counterrotating bulges. However, late accretion of gas-rich satellites could have played a role in the formation of the bulge, as a substantial part of the gas is expected to sink to the center of the potential (Hernquist 1989). Also, even the low mass surface brightness galaxies (Sprayberry et al. 1993) have normal bulges. These galaxies appear to be formed in relative isolation, and are located in low density environments (Bothun et al. 1993), which argues also against bulges formed by late mergers. These galaxies have very young disks, obviously much younger than their bulges. It is reasonable to assume that this is always the case, rather than to assume that bulges can be either older, coeval or younger than disks. This suggests that bulges preceded disks, which are a much colder state of evolution.

7.9. Conclusions

We have studied the kinematics of the halo and bulge in the inner Galaxy, finding that they are very different from each other. The halo has low, constant rotation, and constant velocity dispersion. The bulge has significant rotation, well approximated by a solid body, and its velocity dispersion declines with Galactocentric distance.

The dependence of kinematics on metal abundance in the bulge fields helps explain several other observational facts: the different scale-lengths of different

stellar populations (e.g. Frogel 1988), the different kinematics of different samples (OH-IR stars, Miras, RR Lyraes, planetary nebulae, etc).

The picture of formation of our Galaxy that emerges from the previous considerations is the following. First the halo formed in the way described by Searle & Zinn (1978), with the oldest halo stars being the ones in the inner kpc (Lee 1992). Then the bulge formed dissipationally mostly from material leftover from the halo (Wyse & Gilmore 1992, Carney et al. 1990). Finally, the disk formed $\sim 3\text{-}5$ Gyr after the halo, being ≤ 10 Gyr old (e.g. Janes 1988, Liebert et al. 1988).

Understanding the role of the metal rich globulars is crucial for the development of a consistent picture of Galaxy formation. We argue that these metal rich globulars in the inner Galaxy are associated with the bulge.

8. CONCLUSIONS

Here we summarize the broad major results of this thesis:

- We have presented a large data set, directed to study the kinematics and stellar populations of the Galactic bulge.

- We have succeeded in separating the different Galactic components in low latitude fields. In particular, we have argued that the halo and bulge are two distinct components, having different metallicities and kinematics. This is not a question of semantics. The halo is defined in the Solar neighborhood as being metal poor, and kinematically hot (low rotation and high velocity dispersion). This definition applies globally in the Galaxy, for $R \geq 3$ kpc, as testified by the halo globulars, the field blue HB stars, and the RRLyr variables. In the inner bulge fields we have found a population of stars that have low metallicities, and are kinematically hot. These are undoubtedly halo stars. In contrast, the bulge giants in the same fields exhibit higher metal abundances, higher rotation and lower velocity dispersions, with a strong metallicity gradient and declining velocity dispersion with distance from the Galactic center. The transition between these 2 components occurs at $[\text{Fe}/\text{H}] \sim -1$.

- The bulge giants in field F588 show a clear dependence of kinematics on metallicity, suggesting formation via dissipational collapse. We argue that the bulge formed after the halo. This supports the suggestion of Carney et al. (1990) that the material leftover after the condensation of the halo into stars is

likely to have fallen into the bulge rather than the disk due to its low angular momentum.

- We unveil the kinematics of the bulge as function of Galactocentric distance. The velocity dispersion of bulge K giants decreases with distance, from $\sigma = 100 \text{ km s}^{-1}$ at 0.5 kpc to $\sigma = 60 \text{ km s}^{-1}$ at 1.8 kpc. The velocity dispersion of bulge M giants show similar behavior. The bulge is better described by a solid body rotation than by a constant rotation model.

- We have studied the influence of the thin disk in a low latitude field. The disk contamination can be important at low latitudes, and its kinematics are very difficult to separate from the kinematics of the bulge itself. We find that the line of sight velocity dispersion of the inner disk is indeed larger than that of the Solar neighborhood, confirming the results of Lewis & Freeman (1989). The bulge and the inner disk are also separate entities.

- The halo population was found in all the fields, from 0.5 to 2 kpc. We find that the halo velocity dispersion of this metal poor population is not a strong function of distance, i.e. the halo is approximately isothermal. Constant rotation also provides a good fit for the halo. We estimate that the number of halo relative to bulge giants in the inner Galaxy is typically 10–20 %.

- We argue that the metal rich globulars of the Milky Way are associated mainly with the bulge. This is based mostly on the metallicities and spatial distributions. The kinematics are uncertain, and consistent with both bulge or

the *local* thick disk (but not with the extrapolation of the thick disk into the inner 3 kpc). The ages are more uncertain, and on their basis we cannot rule out similarity with both the *local* thick disk or the bulge. These results support the findings of Frenk & White (1980, 1982).

The association of the inner metal rich globulars also favors a dissipational scenario of formation for the inner Galaxy. The metal rich globulars are younger than the halo globulars (Armandroff 1993), meaning that the bulge is younger than the halo. This result has very interesting implications.

- The dependence of kinematics on metallicity presented also permitted the association of different tracers (PN, M stars, Miras, OH/IR stars, RRLyrs) with different Galactic components. In particular, the RRLyrs belong to the halo and not the bulge, based on their kinematics and metal abundances. Therefore, the presence of RRLyrs at in bulge fields does not mean that the bulge is the oldest Galactic component. The early M giants follow the bulk of the bulge population, while the PN, OH/IR stars, and the Miras have kinematics similar to the most metal rich bulge K giants.

- Using IR photometry, we have confirmed the abundance gradient of the bulge. These data also show that the metal rich globulars (with $[\text{Fe}/\text{H}] \leq -0.6$) have very similar red giant branches as the underlying bulge population, implying similar overall metallicities.

- The mean metallicity of field F588 is $[\text{Fe}/\text{H}] = -0.5$. This is the only field where the selection effects are not important in the metallicity distribution.

Comparing this value with the spectroscopic abundances of McWilliam & Rich (1993), again we see that there is a metallicity gradient, consistent with previous results of Terndrup (1988) and Tyson (1991). The metallicity gradient present in the inner Galaxy is also interpreted as a signature for dissipational collapse.

Further work

Here we describe what would be the next steps for the understanding of the bulge, and its connection to the other Galactic components, including the Galactic center.

- A big improvement will be given by the use of the IR photometry. More accurate distances will be determined, and also effective temperatures by means of the IR flux method.
- The kinematics of an inner field, located in between F588 and Baade's window, are needed to better define the bulge rotation curve. The fields studied by Udalski et al. (1993) for the OGLE experiment are ideal in this respect. These are located at $l, b = (-4.8, -3.5)$, and $(5.4, -3.5)$.
- Determination of ages for bulge giants, trying to establish if there is a large age range, or if the formation of the bulge was very rapid. This can be accomplished with the combination of deep optical and near-IR photometry.
- Determination of relative element abundances, to disentangle the chemical evolution history of the bulge. This will involve the use of modern spectrum

synthesis and model atmospheres, and echelle spectroscopy of selected giants. The He abundance will also be determined as function of Galactocentric radius with the aid of IR photometry.

- Obtain proper motions in off axis fields, to study in depth the 3-D kinematics of the bulge. These data will contribute to refine our knowledge of the formation of the bulge.

APPENDIX 1: A SIMPLE MINDED GALACTIC MODEL

This is a simple working model to estimate the relative numbers of the different components. The point of this exercise is to estimate the relative disk contamination and the distribution of the different Galactic components in the different fields. This is not a complete and self consistent Galaxy model, for some of the necessary ingredients are missing. It should be taken more as a very simplistic view of the Galaxy that happens to fit our data. The model is inspired after the models of Bahcall & Soneira (1983, reviewed by Bahcall 1986), Ruelas Mayorga (1991) and Kent et al. (1991). A model similar to our own is recently used by Morrison (1993). A more complete model of the disk is given by Robin, Creze & Mohan (1992). The differences with these is that we explicitly consider all components of the Galaxy: halo, bulge, thin and thick disk. Considering all these components means that there are many free parameters. The preferred values for the structural constants are noted, as well as their total range as found in the literature. The main caveats are the uncertainties in some of these constants, and the unjustified assumptions that some locally measured quantities (like shapes of the velocity ellipsoids or disk scale-heights) are constant as function of Galactocentric distance. However, we can use this simple model to check the consistency of our arguments. Here then, we define the Galactic components used throughout the thesis, in terms of their metallicities, distributions and kinematics. A stellar population in the Galaxy may be identified by the properties of (1) spatial distribution, (2) kinematics—rotation and velocity dispersion—, (3) metallicity distribution, and (4) ages.

Throughout, we adopt a distance to the Galactic center of $R_0 = 8$ kpc, from Reid (1993). Hereafter, the distance of a star from the Galactic center is given in terms of the star's distance from the Sun R and its Galactic coordinates l , b as:

$$r^2 = R_0^2 + R^2 - 2 R R_0 \cos b \cos l$$

A1.1. THE HALO

The halo density law is:

$$\rho_h = \rho_{h0} r^{-n}$$

where ρ_{h0} can be derived with respect to the disk from counts in the Solar neighborhood, and $n = 3.2$, after Zinn (1985, $n = 3.5$), Saha (1986, $n = 3.0$), and Preston et al. (1992, $n = 3.2$).

The halo kinematics are consistent with an isothermal sphere (this is discussed in chapter III):

$$\sigma_h \approx 110 \text{ km s}^{-1}$$

The halo rotation is taken to be constant:

$$V_h = 40 \text{ km s}^{-1}$$

The halo velocity ellipsoid has axes ratios :

$$\sigma_r : \sigma_\theta : \sigma_\phi = 1.5 : 1.1 : 1.0$$

These values are taken from the compilations of Gilmore (1991), Freeman (1987), Carney et al (1990), Sandage & Fouts (1987), and Norris & Ryan (1991). The halo metallicity can be represented by a gaussian with mean $[\text{Fe}/\text{H}] = -1.6$, and $\sigma_{[\text{Fe}/\text{H}]} = 0.4$, after Norris & Ryan (1991).

A1.2. THE THIN DISK

The old thin disk density law is:

$$\rho_d = \rho_{d0} \exp(-r/h_r) \exp(-z/h_z)$$

where we adopt $h_r = 3.5$ kpc, and $h_z = 0.3$ kpc. That scale-height is appropriate for K and M giants in the Solar neighborhood (e.g. Mihalas & Binney 1981). Locally, an exponential vertical density distribution gives a good description of the star counts (e.g. Pritchett 1983). We assume it remains constant within the Solar circle after van der Kruit & Searle (1982), Shaw & Gilmore (1990). The scale-length of the old thin disk is not certain. Kent, Dame & Fazio (1991) review the different scalelengths measured for the Galactic disk. These range from 1.8 kpc to 5.5 kpc, a factor of 3!. In general, optical studies tend to give larger radial scalelengths than near-IR studies (Kent et al. 1991). The choice of different disk scale-lengths will produce widely different results, this is one of the major objections to a more detailed modeling.

The thin disk kinematics are given by (after Lewis & Freeman 1989, and Norris 1986):

$$V_{rot} = 220 km s^{-1}$$

$$\sigma_r = \sigma_0 \exp(-r/h_r)$$

$$\sigma_r : \sigma_\phi : \sigma_z = 2.0 : 1.4 : 1.0$$

where $\sigma_0 = 35 \exp(R_0/H_r) \text{ km s}^{-1}$.

The mean metal abundance of the thin disk in the Solar neighborhood is $[Fe/H] = -0.3$, with a range from about -0.6 to 0.5 (e.g. Edvarsson et al. 1993).

A1.3. THE THICK DISK

The thick disk density law is:

$$\rho_{tkd} = \rho_{tkd0} \exp(-r/H_r) \exp(-z/H_z)$$

where $H_r = 3.5 \text{ kpc}$, and $H_z = 1 \text{ kpc}$. The scale-length of the thick disk is less well known than the scale-length of the thin disk. Gilmore (1991) proposes that $H_r = h_r$ for the lack of a better assumption. Also, Ratnatunga & Freeman (1989) find that the extensions of the thin and thick disk are comparable.

The thick disk kinematics are given by (e.g. Norris & Ryan 1991):

$$V_{rot} = 180 km s^{-1}$$

$$\sigma_r = \sigma_0 \exp(-r/H_r)$$

$$\sigma_r : \sigma_\phi : \sigma_z = 1.7 : 1.3 : 1.0$$

where $\sigma_0 = 100 \exp(R_0/H_r)$ km s⁻¹. Note that this law predicts unreasonable large σ for decreasing Galactocentric distances. A better assumption might be to take a constant value for the velocity dispersion of the thick disk.

The mean abundance of the thick disk is $[Fe/H] = -0.6$, with a total range from about -1.5 to -0.3 (Gilmore & Wyse 1985, Norris & Ryan 1992, Carney et al. 1990, Edvarsson et al. 1993).

A1.4. THE BULGE

The bulge density law is:

$$\rho = \rho_0 r^{-N}$$

where $N = 3.7$, and $r^2 = r^2 \sin^2 \theta + r^2 \cos^2 \theta / \epsilon^2$ (θ is the polar angle in spherical coordinates). Table A1 lists existing determinations of N . We note that the oblate isotropic rotator model for the bulge of Kent (1992) can be approximated by a simple power law model (DeZeeuw 1993). The bulge is assumed to be flattened, with a minor-to-major axis ratio $\epsilon = 0.7$.

The bulge kinematics are (from this thesis):

$$V_m = A \text{ l km s}^{-1}$$

$$\sigma_{los} = 120r^{-B} \text{ km s}^{-1}$$

$$\sigma_r : \sigma_\theta : \sigma_\phi = 1.2 : 1.0 : 1.0$$

The mean dependences for the bulge are : $A = 10$, $B = -0.35$. The trends with metallicity are represented by: $\Delta A / \Delta[Fe/H] = 0.05$, and are discussed in chapter 7.

The axes ratios given above are local, but are assumed to be constant with Galactocentric distance, except for the bulge where the axes ratios are measured in situ by Spaenhauer et al. (1992) and in chapter 5.

A1.5. NORMALIZATIONS

The normalization of the different components is the biggest uncertainty. The normalization adopted at the Solar distance $R = 8$ kpc is:

$$N_d : N_{tkd} : N_h = 1.0 : 0.02 : 0.002$$

after Norris (1987), and Carney et al. (1990). Using these values and the density laws described above, we assume that the number of disk giants at the

Solar circle per arbitrary unit of volume is $\rho_{d0} = 10$. Thus, $\rho_{h0} = 0.02$, $\rho_{tkd0} = 0.2$.

As noted below, these normalizations fail to reproduce the observations.

The bulge is normalized to the halo assuming $N_h/N_b(1.5 \text{ kpc}) = 20\%$ observed at F588 (c.f. chapter 5). We assume that the bulge is mostly confined to the inner 2 kpc, after the COBE and IRAS maps (e.g. Kent et al. 1991, Habing et al. 1985, Harmon & Gilmore 1988, Weiland et al. 1993). Note that if the number of halo giants had a similar dependence as the number of bulge giants (i.e. if both obey $r^{-3.5}$), the relative contributions of these two components will be constant, independent of distance. Even though there were different selection processes involved in the selection of the samples, we can discard this hypothesis, due to the fact that at $N_h / N_{total} \approx 0.1$, 0.2, and 0.2 at the BW, F588, and F589 fields, respectively (for this estimate we call halo stars all the stars with $[\text{Fe}/\text{H}] \leq -1.25$).

These laws are valid from 0.3 to 8 kpc, except for the bulge, which is not extended further than $\sim 2 - 3$ kpc from the Galactic center. Also, inside of 0.3 kpc the bulge obeys a much shallower power law ($r^{-1.8}$, e.g. Kent 1992). Outside of 8 kpc the density laws are mostly unknown (i.e. disk flare-up, warped).

A1.6. THE ABSORPTION

The absorption law in the Galactic disk is (in magnitudes):

$$A = A_0 \exp(-(r - R_0)/h_r^a) \exp(-z/h_z^a)$$

where $A_0 = 1.0$ and $0.08 \text{ mag kpc}^{-1}$ for the V and K bands, respectively. The absorption scale-length is taken to be $h_r^a = 3.5 \text{ kpc}$, the same as the disk scale-length. The absorption scale-height is taken to be $h_z^a = 0.1 \text{ kpc}$ (e.g. Ruelas Mayorga (1991)). Figure A1 shows the extinction as function of distance from the Sun for the different fields studied. The total extinction has been scaled to the observed reddenings: $E(B-V) = 0.18$ for F588, $E(B-V) = 0.45$, and 0.90 for window and reddened parts of field F589, respectively, and $E(B-V) = 0.32$ for the M22 field. We have adopted the reddening law of Rieke & Lebofski (1983) that gives $A_V = 3.1 E(B-V)$, and $A_K = 0.346 E(B-V)$. Figure A1 shows that for all the fields most of the obscuration occurs within 2.5 kpc of the Sun, except for the reddened part of field F589, (the reddened part of F589 is at lower latitude than the F589 window) where significant reddening contributions are within 4 kpc. Figure A1 shows that different reddenings should be of no concern for the determination of distances to bulge giants.

A1.7. LUMINOSITY FUNCTIONS

Whenever needed, for the halo and disk we adopt the V luminosity functions from Bahcall & Soneira (1984):

$$\phi(M) = 1.28 \cdot 10^{0.04(M-1.28)} / (1 + 10^{-2.38(M-1.28)})^{3.4}$$

which can be approximated for $M \leq -1.0$ as:

$$\phi(M) \approx \phi_0 M^{0.67}$$

Figure A1: Absorption in K as function of distance for the different fields.

The absolute magnitude M depends on the apparent magnitude m , the distance R , and the absorption A :

$$M = m - 5\log R - A(R) + 5$$

A1.8. CONTRIBUTIONS ALONG THE LINE OF SIGHT

With all the parameters and density laws discussed above, we can look at the contributions from the different Galactic components as function of distance along the line of sight for every field studied here. The BW field is included for comparison. Figures A2 to A5 show the number of bulge (dotted line), halo (solid line), thin disk (upper dashed line), and thick disk (lower dashed line) as function of distance from the Sun. We recall that $R_0 = 8$ kpc. Note that the density distributions are not symmetric with respect to $R = 0$ due to the R^2 solid angle factor. The numbers in the ordinate of these figures are not arbitrary, they are scaled to give 10 disk giants per unit volume in the Solar neighborhood. Thus, the relative numbers in the different fields are meaningful.

The normalizations adopted are valid for *giants* of the different components. The only dwarfs that will be present are the thin disk dwarfs, which will follow the also the upper dashed line in figures A2–A5, but with a larger normalization. From Bahcall & Soneira (1980) and Ruelas Mayorga (1991) the ratio of disk K dwarfs to K giants at the Solar circle is 30–40. The majority of spectra taken in bulge fields have spectral type K, with only about 5% of M stars. The G8–K3 V dwarfs have a mean magnitude $V \sim 6.0$. Since our spectroscopy does not

Figure A2: Number of giants belonging to the bulge (dotted line), the halo (solid line), the thin disk (upper dashed line) and the thick disk (lower dashed line) as function of distance along the line of sight for F588. The solid angle factor R^2 is included.

Figure A3: Same as figure 2 for field F589.

Figure A4: Same as figure 2 for field M22.

Figure A5: Same as figure 2 for field BW.

include stars with magnitudes $R \leq 14.5$, only K dwarfs within 500 pc from the Sun will be included in our sample. Scaling the disk density law in figures A2–A5 by a factor of 40, we see that still the number of potential disk dwarfs is negligible compared to giants in all fields.

However, due to the color–color and magnitude cuts of the present sample, the disk dwarfs within 2 kpc are an insignificant contribution also. The first striking result from these figures is that the contribution from the thick disk is insignificant in all the fields. The halo amounts only to 10–20 % of the bulge giants in all the field, due to our normalization at F588. Figures A2–A5 also show that the thin disk peaks at shorter distances than the bulge and halo. The magnitude cutoffs applied to the samples will include preferentially K giants with distances within $6 \leq D \leq 10$ kpc from the Sun. This helps to exclude a large number of close disk giants, favoring bulge stars.

A1.8.1. Discussion of individual fields

The BW field is predicted by the model to be dominated by bulge giants, with ~ 10 % and ~ 5 % contamination from halo and disk giants, respectively.

Field F588 and M22 have about the same relative contributions from the different components, due to their similar locations with respect to the Galactic center and plane, even though they are in different quadrants. The total number of halo stars with respect to bulge stars is ~ 20 %. Excluding the disk giants with $D \leq 6$ kpc, the total number of disk giants with respect to bulge giants is ~ 30 %. This value is too high compared with the IR observations and models of Kent et al. (1991).

Finally, field F589 is predicted to be dominated by disk giants, which outnumber the bulge giants by a factor of ~ 4 within $6 \leq D \leq 10$ kpc. The halo appears not to be important here, amounting to ~ 20 % of the bulge. These predictions are contrary to the photometric evidence. The color-magnitude diagrams presented in chapter show that there are large numbers of disk giants, but the bulge contributes significantly for magnitudes $R \geq 12.5$. There is also a sharp increase of the luminosity function (not shown here) in this field at the expected location of the bulge AGB tip. Also, the number of metal poor halo stars detected in F589 is ~ 20 %, far larger than predicted by the model, even though some selection effects might be present. Furthermore, the surface photometry and modeling of Kent et al. (1991) predict that the bulge is larger than the disk contribution in this field.

The choice of a different scale-length for the disk is not enough to solve the problem, the different normalizations must be in error. We have decided then to check this problem by counting stars in the different fields.

A1.9. IR STARCOUNTS IN BULGE FIELDS

Along with the IR photometry of clusters presented in chapter 2, we have observed also the fields F588, F589, BW, and Sgr1. We will not discuss this photometry further, only to give the star counts in these fields to try to solve the problem encountered with the relative numbers of bulge to disk giants in F589.

We have constructed deep K luminosity functions for these fields. We chose to count stars within 1 magnitude interval centered at 1 magnitude above the

peak of the HB. The counts are complete in that interval for all the fields studied. Furthermore, the HB gives an excellent point of reference, determining that the number counts are going to be independent of reddening. This is not true for the surface photometry maps of the bulge, which we can also check to constrain the contributions from different components. Table A2 column 5 shows the star counts, in number of giants per magnitude per square degree at 1 magnitude brighter than the HB ($K \sim 11$). Column 6 gives the total number of giants normalized to BW. We would like to stress the fact that these counts are robust, independent of reddening, photometric errors, and distribution along the line of sight. Also listed in table A2 are the K surface brightness measurements of Kent et al. (1991), and the respective expected total number of giants normalized to BW. The agreement between the integrated photometry and the number counts is reassuring.

Table A2 shows that the total number of giants at F589 with respect to F588 is on the order of $N_{F589}/N_{F588} \approx 1.4$, much smaller than the ratio ~ 5 predicted by the model (figure A5). One way to solve the problem is to adopt different disk/halo and disk/bulge normalizations, keeping the bulge/halo normalization that seems to agree with the observations. For that, we find that increasing the bulge–halo giants by a factor of 5 brings into agreement the photometry with the model and the spectroscopy. This arbitrary normalization is not surprising, given all the caveats to the model presented at the beginning of this chapter.

At the same time, note that this particular choice of parameters brings into agreement our estimate of disk/bulge ratio in Baade’s window with those

of Terndrup & Blanco (1989), Terndrup (1988), Rich (1988, 1990) and Tyson (1991 –even though we estimate fewer dwarfs here than Tyson–). All these works estimate disk/bulge $\leq 5\%$ at Baade’s window.

A1.10. FINAL MODELS

Therefore, the final adopted density distributions are shown in figures A6 to A9. The final relative contributions of the different components within $6 \leq D \leq 10$ kpc for each field are summarized in table A3. These are the numbers that we will consider in the chapters discussing the individual fields. However, in these chapters we have to take into account also the color selection, which will be different for each field.

To summarize, a simple model including all Galactic stellar components (thin and thick disk, halo and bulge) was constructed. It was found that the large uncertainties in the parameters imply a wide range of results. In particular, changing the scalelengths or normalizations we find that the fields studied in this thesis can be completely dominated by either bulge or disk stars (i.e. we can obtain any result we want). We have chosen a particular set of parameters that describe our data well, with the aid of star counts in the near-IR. We have then estimated the relative contributions and distributions along the line of sight for all the Galactic components in the different fields studied.

Table A.1 DENSITY LAW EXPONENTS FOR THE BULGE

STARS	N	REFERENCE
K + M	3.65	Terndrup 1988
M2 or later	3.7	"
M5 or later	4.2	"
LPV's	3.66	Terndrup et al. 1991
K integ.	3.63	"
V integ.	3.54	"
IRAS sources	4.8	Harmon & Gilmore 1988

Table A.2 : IR STAR COUNTS IN BULGE FIELDS

Field	l	b	Rgal	N/deg	N/NBW	Kint	N/NBW
Sgr1	0	-3	0.42	31400	1.46	15.8	1.30
BW	1	-4	0.56	21522	1.00	16.0	1.00
F589	11	3	1.71	6426	0.30	16.9	0.40
F588	8	7	1.48	3978	0.18	17.6	0.25
M22	10	-8	1.73	----	----	17.8	0.20

Table A.3 CONTRIBUTIONS FROM DIFFERENT COMPONENTS

Field	Nd	Ndd	Ntkd	Nh	Nb
BW	3%	---	---	10%	87%
F588	3%	---	---	20%	77%
F589	35%	<3%	2%	15%	45%
M22	5%	---	1%	20%	74%

Figure A6: Number of giants belonging to the bulge (dotted line), the halo (solid line), the thin disk (upper dashed line) and the thick disk (lower dashed line) as function of distance along the line of sight for F588 for the final model with the increased bulge and halo.

Figure A7: Same as figure 6 for field F589.

Figure A8: Same as figure 6 for field M22.

Figure A9: Same as figure 6 for field BW.

REFERENCES

- Aguilar, L., Hut, P., & Ostriker, J. P. 1988, *ApJ*, 335, 720
- Alcaino, G. 1977, *A&A*, 29, 383
- Alcaino, G. 1980, *A&AS*, 39, 315
- Alcaino, G. 1981, *A&AS*, 44, 33
- Alcaino, G., & Liller, W. 1983, *AJ*, 88, 1330
- Alcaino, G., & Liller, W. 1984, *ApJS*, 56, 19
- Armandroff, T. 1993, in *Proceedings of the Santa Cruz Summer Workshop "The Globular Cluster-Galaxy Connection"*, eds J. Brodie and G. Smith (ASP), p. 48
- Armandroff, T. E. 1988, *AJ*, 96, 588
- Armandroff, T. E. 1989, *AJ*, 97, 375
- Armandroff, T. E., & DaCosta, G. S. 1991, *AJ*, 101, 1329
- Armandroff, T. E., & Zinn, R. 1991, *AJ*, 96, 92
- Arnett, W. D. 1978, *ApJ*, 219, 1008
- Arnett, W. D. 1993, *Supernovae and Nuclei*, in press
- Arp, H. C. 1955, *AJ*, 60, 317
- Arp, H. C. 1959, *AJ*, 64, 33
- Arp, H. C. 1965, *ApJ*, 141, 43
- Arp, H. C., & Melbourne, W. G. 1959, *AJ*, 64, 28
- Azzopardi, M., Lequeux, J., & Reberiot, E. 1985, *AA*, 145, L4
- Azzopardi, M., Lequeux, J., & Reberiot, E. 1988, *AA*, 202, L27
- Azzopardi, M., Lequeux, J., Reberiot, E. & Westerlund, B. E. 1991, *AAS*, 88, 265

- Baade, W. 1944a, ApJ, 100, 137
- Baade, W. 1944b, ApJ, 100, 147
- Baade, W. 1951, Publ. Obs. Univ. Michigan No. 10, 7
- Bahcall, J. N., 1986, ARA&A, 24, 577
- Bahcall, J. N., & Soneira, R. M. 1980, ApJS, 44, 73
- Bahcall, J. N., & Soneira, R. M. 1984, ApJS, 55, 67
- Barbuy, B., & Grenon, M. 1990, in "Bulges of Galaxies", eds B. Jarvis and D. Terndrup (ESO: Garching), p. 47
- Barbuy, B., Castro, S., Ortolani, S., and Bica, E. 1992, A&A, 259, 607
- Barbuy, B., Erdelyi-Mendes, M., & Milone, A. 1993, A&AS, 93,235
- Barnes, J., and White, S.D.M. (1984) MNRAS 211 753
- Baum, W., Light, R. M., Holtzman, J., Hunter, D., Kreidl, T., O'Neil, E. J., & Groth, E. J. 1993, in IAU Symp. 153 "Bulges of Galaxies", eds. H. Habing & H. DeJonghe (Dordrecht: Kluwer), in press
- Bell, R. A. 1992, MNRAS, 257, 423
- Bell, R. A., and Gustafsson, B. 1989 MNRAS 236 653
- Bergbush, P. A., and VandenBerg, D. A. 1992, ApJS, 81, 163
- Bertola, F., Rubin, V., and Zeilinger, W. 1989, ApJ 345, L29
- Bertola, F., and Cappaccioli, M. 1975, ApJ 200, 439
- Bessell, M. S., Brett, J. M., Scholz, M., & Wood, P. R. 1989, AAS, 77, 1
- Bessell, M. S., Brett, J. M., Scholz, M., & Wood, P. R. 1991, AAS, 89, 335
- Bica, E., Barbuy, B., and Ortolani, S. 1991, ApJ, 382,L15
- Binney, J. 1978, MNRAS, 183, 501
- Binney, J. 1982, ARA&A 20, 399

- Binney, J., and Tremaine, S. 1987 in 'Galactic Dynamics', (Princeton Univ. Press, Princeton N.J.), p. 276
- Blaauw, A. 1965, in Galactic Structure, Stars and Stellar Systems Vol. 5, eds. A. Blaauw & M. Schmidt (Chicago: Univ. of Chicago Press), p. 435
- Blanco, V. 1965, in Galactic Structure, Stars and Stellar Systems Vol. 5, eds. A. Blaauw & M. Schmidt (Chicago: Univ. of Chicago Press), p. 241
- Blanco, V. M. 1988, AJ, 91, 290
- Blanco, V. M. 1988, AJ, 95, 1400
- Blanco, V. M., McCarthy, M. F., & Blanco, B. M. 1984, AJ, 89, 636
- Blanco, V. M., and Terndrup, D. M. (1989) A.J. 98 843
- Blanco, B. 1992, AJ, 103, 1872
- Blanco, B. 1984, AJ, 89, 1836
- Bothun, G. D. 1992, AJ, 103, 104
- Bothun, G. D., Schombert, J. M., Impey, C. D., & Sprayberry, D. 1993, AJ, 106, 530
- Bottema, R. 1993, AA, 275, 16
- Brodie, J. P. & Huchra, J. P. 1990, ApJ, 362, 503
- Burstein, D., Faber, S., Gaskell, M., & Krumm, N. 1984, ApJ, 287, 586
- Burton, W. B. 1976, ARA&A, 14, 275
- Burton, W. B. & Gordon, M. A. 1978, AA, 63, 7
- Buzzoni, A. 1989, ApJS, 71, 817
- Canterna, R., 1976, AJ, 81, 228
- Carney, B. W. 1990, in "Bulges of Galaxies", eds B. Jarvis and D. Terndrup (ESO: Garching), p. 26
- Carney, B. W., Latham, D. W., and Laird, J. B. 1989, AJ, 97, 823

- Carney, B. W., Latham, D. W., and Laird, J. B. 1990, *AJ*, 99, 752
- Carney, B. W., Storm, J., & Jones, R. V. 1992, *ApJ*, 386, 663
- Carney, B. W. 1993, in *ASP Conf. Series Vol. 49 Galaxy Evolution: The Milky Way Perspective*, ed. S. R. Majewski (ASP), p. 209
- Catchpole, R. M. 1990, in *Proceedings of the ESO-CTIO Workshop on Bulges of Galaxies*, eds. B. J. Jarvis & D. M. Terndrup (Garching: ESO), p. 111
- Catchpole, R. M., Whitelock, P. A., & Glass, I. S. 1990, *MNRAS*, 247, 479
- Catelan, M., & Freitas Pacheco, J. A. 1993, *AJ*, 106, 1858
- Christian, C. A., & Friel, E. D. 1992, *AJ*, 103, 142
- Cook, K. 1987, Ph.D. Thesis, Steward Observatory, Univ. of Arizona
- Croswell, K., Latham, D. W., Carney, B. W., Schuster, W., & Aguilar, L. 1991, *AJ*, 101, 2078
- Cuddeford, P., & Amendt, P. 1992, *MNRAS*, 256, 166
- Cudworth, K. M. 1986, *AJ*, 92, 348
- Cudworth, K. M., and Peterson, R. C. 1988 in 'Globular Cluster Systems in Galaxies', *IAU Symp. No. 126*, eds J. Grindlay and A.G.D. Philip (Reidel, Dordrecht), DaCosta, G. S., Mould, J. R., & Ortolani, S. 1984, *ApJ* 282, 125
- DaCosta, G. S., & Armandroff, T. A. 1990, *AJ*, 100, 162
- DaCosta, G. S., & Seitzer, P. 1989, *AJ*, 97, 405
- Davidge, T. J. 1991, *ApJ* 380, 116
- Davidge, T. J., Harris, W. E., Bridges, T. J., & Hanes, D. A. 1992, *ApJS*, 81, 251
- Davidge, T. J., & Simmons, D. A. 1991, *AJ* 101, 1760
- Davies, R. L., Frogel, J. A., & Terndrup, D. M. 1991, *AJ*, 102, 1729
- Delhaye, J. L. (1954), in "Galactic Structure", eds. A. Blaauw and M. Schmidt, (Univ. of Chicago Press, Chicago) p. 1

- Demarque, P., Green, E. M., & Guenther, D. B. 1992, AJ, 103, 151
- Demarque, P., & Lee, Y. W. 1992, AA, 265, 40
- DePoy, D. L., Terndrup, D. M., Frogel, J. A., Atwood, B., & Blum, R. 1993, AJ in press
- de Vaucouleurs, G. 1964, in IAU Symp. 20 "The Galaxy and the Magellanic Clouds", eds. F Kerr & A. Rodgers, (Aust. Acad. of Science) p. 195
- de Vaucouleurs, G., & Pence, W. D. 1978, AJ, 83, 1163
- Djorgovski, G. 1993, in Proceedings of the Berkeley Workshop on Structure and Dynamics of Globular Clusters, eds. G. Meylan and G. Djorgovski, (ASP Conf. Series No. 50), p. 373
- Drake, J. J., Smith, V. V., & Suntzeff, N. B. 1992, ApJ, 395, L95
- Edvarsson, B., Andersen, J., Gustafsson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, AA, 275, 101
- Eggen, O. J. 1972, ApJ, 172, 639
- Eggen, O. J., Lynden-Bell, D., and Sandage, A. 1962, ApJ, 136, 748
- Elias, J. H., Frogel, J. A., Matthews, K., & Neugebauer, G. 1988, AJ, 87, 1029
- Elston, R., & Silva, D. R. 1992, AJ, 104, 1360
- Faber, S. M., Friel, E. D., Burstein, D., and Gaskell, C. M. (1985) Ap.J. Suppl. 57 711
- Feast, M. W. 1987, in The Galaxy, eds. G. Gilmore & R. Carswell (Reidel: Dordrecht), p. 1
- Feast, M. W., Robertson, B. S. C., and Black, C. 1980, MNRAS, 190, 227
- Feast, M. W., & Whitelock, P. A., 1987, in Late Stages of Stellar Evolution, eds. S. Kwok & S. Pottasch (Reidel: Dordrecht), p. 33
- Feast, M. W., Whitelock, P. A., & Sharpless, R. 1992, in IAU Symp. 149 "The Stellar Populations of Galaxies", eds B. Barbuy & A. Renzini (Kluwer: Dordrecht), p. 77
- Ferraro, F., Fussi Pecci, R., Guarnieri, M. D., 1993, MNRAS in press

- Francois 1991, A&A, 247, 56
- Freedman, W. L. 1992, AJ, 104, 1349
- Freeman, K. 1987, ARA&A 25, 603
- Freeman, K. 1988, in *Astrophysics: Recent Progress and Future Possibilities*, eds B. Gustafsson & P. E. Nissen (Munksgaard: Copenhagen), p. 187
- Freeman, K. 1989, in *Dynamics of Disk Galaxies*, ed. B. Sundelius (Gottaborg: Sweden), p. 1
- Freeman, K. C., de Vaucouleurs, G., de Vaucouleurs, A., and Wainscoat, R. J. (1988) Ap.J. 325 563
- Frenk, C. S., and White, S. D. M. 1980, MNRAS 193, 295
- Frenk, C. S., and White, S. D. M. 1982, MNRAS 198, 173
- Friel, E. D. 1987, AJ, 93, 1388
- Friel, E. D., Liu, T., & Janes, K. A. 1989, PASP, 101, 1105
- Friel, E. D., & Janes, K. A. 1993, A&A, 267, 75
- Friel, E., and Janes, K. 1993, A&A, 267, 75
- Frogel, J. A. 1988, ARA&A 26, 51
- Frogel, J. A. 1990, in *Bulges of Galaxies*, eds. B. Jarvis and D.M. Terndrup (ESO: Garching), p. 111
- Frogel, J. A., Cohen, J. G., & Persson, S. E. 1983, ApJ, 275, 773
- Frogel, J. A., Persson, S. E., & Cohen, J. G. 1983, ApJS, 53, 713
- Frogel, J., A., Persson, S. E., & Cohen, J. G. 1981, ApJ, 246, 842
- Frogel, J., A., Terndrup, D. M., Blanco, V. M., & Whitford, A. E. 1990, ApJ, 353, 494
- Frogel, J. A., & Whitford, A. E. 1987, ApJ, 320, 199
- Frogel, J. A., Whitford, A. E., & Rich, R. M. 1984, AJ, 89, 1536

- Geisler, D., Claria, J. J., & Minniti, D. 1991, AJ, 102, 1836
- Geisler, D., Claria, J. J., & Minniti, D. 1992, AJ, 104, 1892
- Geisler, D., and Friel, E. D. 1990, AJ, 104, 128
- Gerhard, O. E., & Vietri, M. 1986, MNRAS, 223, 377
- Gilmore, G. 1990 in 'The Milky Way as a Galaxy', eds. R. Buser and I. King, (Univ. Science Books, California), pp. 11, 31, 232
- Gilmore, G., & Reid, I. N. 1983, MNRAS, 202, 1025
- Gilmore, G., & Wyse, R. 1985, AJ, 90, 2015
- Gilmore, G., & Wyse, R. 1986, Nature, 322, 806
- Gilmore, G., Wyse, R., and Kuijken, K. 1989, ARA&A 27, 555
- Glass, I. S. 1993, in Nuclei of Normal Galaxies: Lessons from the Galactic Center, Nato ASI Series (Kluwer: Dordrecht), in press
- Gorgas, J., Faber, S. M., Burstein, D., Gonzalez, J. J., Courteau, S., & Prosser, C. 1993, ApJS, 86, 153
- Gratton, R. G. 1987, MNRAS, 224, 175
- Green, E. M., & Norris, J. E. 1990, ApJ, 353, L17
- Grenon, M. 1989, Ap&SS, 156, 29
- Grenon, M. 1990, in Elba Workshop " Chemical & Dynamical Evolution of Galaxies"
- Gulati, R. K., Malagnini, M. L., & Morossi, C. 1993, ApJ, 413, 166
- Gunn, J., Knapp, R., and Tremaine, S. (1979) A.J. 84 1181
- Habing, H. J., 1988, A&A 200, 40
- Habing, H. J., Olmon, F. M., Chester, T., Gillet, F., Rowan-Robinson, M., and Neugebauer, G. 1985, A&A 152, L1
- Haller, J. W. 1992, Ph.D. Thesis, University of Arizona, Tucson

- Harmon, R. , and Gilmore, G. 1988, MNRAS 235, 1025
- Harris, H. 1993, AJ, 106, 604
- Harris, W. E. 1975, ApJS, 29, 397
- Harris, W. E., & Racine, R. 1979, ARA&A, 17, 241
- Hartwick, F. D. A. 1976, ApJ, 209, 418
- Hauser, M. G. 1993, in Back to the Galaxy, AIP Conf. Proc. No. 278, eds. S. S. Holt & F. Verter (AIP: New York) p. 201
- Hauser, M. G., et al. 1990, NASA Photograph G90-03046
- Hazen, M., et al. 1993, AJ, 105, 557
- Hernandez-Pajares, M. 1993, MNRAS, 264, 1
- Hernquist, L. 1989, Nature, 340, 687
- Herschell, J., 1847, in Results of the Astronomical Observatory at the Cape of Good Hope, London.
- Hesser, J. E., Harris, W. E., Vandenberg, D. A., Allwright, J. W. B., Schott, P., & Stetson, P. B. 1987, PASP, 99, 739
- Hesser, J. E., Shawl, S. J., & Meyer, J. E. 1986, PASP, 98, 403
- Hesser, J., & Shawl, S. 1985, PASP, 97, 465
- Hill, J. M., and Lesser, M. P. 1986, in "Proceedings of SPIE Conference on Instrumentation in Astronomy VI", 627, 303
- Hill, J. M., and Lesser, M. P. 1988, in "Instrumentation for Ground-Based Optical Astronomy: Present and Future", ed. L. B. Robinson (Springer-Verlag, New York) p. 233
- Hodder, P. J. C., Nemec, J. M., Richer, H. B., & Fahlman, G. G. 1992, AJ, 103, 460
- Holtzman, J., Light, R. M., Baum, W. A., Worthey, G., Faber, S. M., Hunter, D., O'Neil, E. J., Kreidl, T., Groth, E. J. & Westphal, J. A. 1993, AJ, 106, 1826

- Horch, E., Demarque, P., & Pinsonneault, M. 1992, *ApJ*, 388, L53
- Hubble, E. P. 1936, *The Realm of the Nebulae* (New Haven: Yale Univ. Press)
- Illingworth, G., and Schechter, P. 1982, *ApJ* 256, 481
- Irwin, M. 1989, private communication
- Janes, K. A. 1979, *ApJS* 39, 135
- Janes, K. 1975, *ApJS*, 29, 161
- Janes, K. A. 1978, *ApJ*, 243, 135
- Janes, K. A. 1988, in *Calibrating Stellar Ages*, ed. A.G.D. Philip (Schenectady: L. Davis Press), p. 59
- Johnson, H. L. 1966, *ARAA*, 4, 193
- Kapteyn, J. C., & Van Rhijn, P. J. 1920, *ApJ*, 52, 23
- Katz, N. (1989) PhD Thesis, Univ. of Princeton.
- Kennicutt, R. 1983, *ApJ*, 272, 54
- Kent, S. M. 1989, *AJ*, 97, 1624
- Kent, S. M. 1992, *ApJ*, 387, 181
- Kent, S. M. 1992, private communication
- Kent, S. M., Dame, T. M., & Fazio, G. 1991, *ApJ*, 378, 496
- Kinman, T. D. 1959, *MNRAS*, 119, 559
- Kinman, T. D., Feast, M. W., and Lasker, B. M. (1988) *A.J.* 95 804
- Knude, J. 1993, *AA*, 275, 463
- Kormendy, J., and Illingworth, G. 1982, *ApJ*, 256, 460
- Kormendy, J., 1993, in *IAU Symp. 153 "Bulges of Galaxies"*, eds. H. Habing & H. DeJonghe, in press

- Kruit, P. C. van der 1990 in 'The Milky Way as a Galaxy', eds. R. Buser and I. King, (Univ. Science Books, California), p. 96
- Kruit, P. C. van der, & Searle, L. 1981, AA, 95, 105
- Kruit, P. C. van der, & Searle, L. 1982, AA, 110, 61
- Laird, J. B., Carney, B. W., & Latham, D. W. 1988, AJ, 95, 1843
- Larson, R. B. 1976, MNRAS, 176, 31
- Layden, A. 1993, in Proceedings of the Santa Cruz Summer Workshop "The Globular Cluster-Galaxy Connection", eds J. Brodie and G. Smith (ASP), p. 326
- Lee, Y. W. 1992, AJ, 104, 1780
- Levison, H. F., & Richstone, D. O. 1986, ApJ, 308, 627
- Lewis, J. R., & Freeman, K. C. 1990, AJ 97, 139
- Liebert, J., Dahn, C. C., & Monet, D. G. 1988, ApJ, 332, 891
- Liller, M. H. 1980, AJ, 85, 673
- Lin, D. N. C., & Richer, H. B. 1992, ApJ, 388, L57
- Lindblad, B. 1927, MNRAS, 87, 553
- Lloyd Evans, T. 1975, MNRAS, 171, 647
- Long, K., Ostriker, J. P. & Aguilar, L. 1992, ApJ, 388, 362
- Maciel, W. J., & Dutra, W. J. 1992, A&A, 262, 271
- Maffeo, S. 1991, In the Service of Nine Popes (Specola Vaticana: Vatican), p. 14
- Malkan, M., 1981, in Astrophysical Parameters for Globular Clusters, IAU Colloquium No. 68, eds. A. G. D. Philip & D. S. Hayes (Davis: Schenectady), p. 533
- Malkan, M., Kleinmann, D. E., & Apt, J. 1980, ApJ, 237, 432
- Malmquist, K. G. 1936, Stockholm Obs. Medd. No. 26

- Martins, D. H., Harvell, C. A., & Miller, D. H. 1980, *AJ*, 85, 521
- Mather, J.C., et al. 1990, in *Observatories in Earth Orbit and Beyond*, ed. Y. Kondo, Kluwer:Dordrecht, p. 9
- Matteucci, F. 1993, personal communication
- Matteucci, F. & Brocato, E. 1990, *ApJ*, 365, 539
- Mayall, N. U. 1946, *ApJ*, 104, 290
- Mayor, M. et al. 1984, *A&A*, 134, 118
- McWilliam, A. 1990, *ApJS*, 74, 1075
- McWilliam, A., & Rich, R. M. 1993, *ApJS*, in press
- Menzies, J. W. 1990, in *Proceedings of the ESO-CTIO Workshop on Bulges of Galaxies*, eds. B. J. Jarvis & D. M. Terndrup (Garching: ESO), p. 111
- Mighell, K., & Rich, R. M. 1993, *ApJ*, in press
- Mihalas, D., & Binney, J. 1981, *Galactic Astronomy* (San Francisco: Freeman)
- Minniti, D. 1993, in *IAU Symp. 153 "Bulges of Galaxies"*, eds. H. Habing & H. DeJonghe, in press
- Minniti, D., Coyne, G. V., & Claria, J. J. 1992, *AJ*, 103, 871
- Minniti, D., Olszewski, E., and Rieke, M., 1993a, *ApJ*, 410, L79
- Minniti, D., Peterson, R. C., Geisler, D., & Claria, J. J. 1993, in *Proceedings of the Santa Cruz Summer Workshop "The Globular Cluster-Galaxy Connection"*, eds J. Brodie and G. Smith (ASP), p. 210
- Minniti, D., Rieke, M., and Olszewski, E., 1993b, (in preparation)
- Minniti, D., White, S.D.M., Olszewski, E., Hill, J., and Irwin, M., 1991, in *Proceedings of the IAU Symp 149 "Stellar Populations"*, Eds. A. Renzini and B. Barbuy (Kluwer: Dordrecht), p. 459
- Minniti, D., White, S.D.M., Olszewski, E., and Hill, J.H. 1992a, *ApJ*, 393, L47
- Morgan, W. W., Keenan, P. C., & Kellman, E. 1943, "An Atlas of Stellar Spectra" (Astrophysical Monographs: Chicago)

- Morgan, W. W., & Mayall, N. U. 1957, PASP, 69, 291
- Morrison, H. L., Flynn, C., and Freeman, K. C. 1990, AJ 100, 1191
- Morrison, H. L., 1993, AJ 105, 539
- Morrison, H. L., 1993, AJ 106, 578
- Morrison, H. L., & Harding, P. 1993, in IAU Symp 153 Galactic Bulges, eds. H. Habing & H. DeJonghe (Dordrecht: Kluwer), in press
- Morrison, H. L., & Harding, P. 1993, PASP, 105, 977
- Mould, J. R. 1982, ARAA, 20, 91
- Mould, J. R. 1983, ApJ 266, 255
- Nakada, Y., Deguchi, S., Hashimoto, O., Izumura, H., Onaka, T., Sekiguchi, K., & Yamamura, I. 1991, Nature, 353, 140
- Nakada, Y., Onaka, T., Yamamura, I., Deguchi, S., Ukita, N., & Izumura, H. 1993, PASJapan, 45, 179
- Nassau, T., & Blanco, V. M. 1958, ApJ, 128, 46
- Neese, C. L., & Yoss, K. M. 1988, AJ, 95, 463
- Nomoto, K., Thielemann, F., & Yokoi, Y. 1984, ApJ, 286, 644
- Nomoto, K., Tsujimoto, T., & Wanajoh, S. 1992, Univ. of Tokio preprint No. 92-2
- Norman, C. 1993, in IAU Symp. 153 "Bulges of Galaxies", eds. H. Habing & H. DeJonghe, in press
- Norris, J. E., Bessell, M. S., & Pickles, A. J. 1985, ApJS 58, 463
- Norris, J. E. 1986, ApJS, 61, 667
- Norris, J. E. 1987, ApJ, 314, L39
- Norris, J. E., & Green, E. M. 1989, ApJ, 337, 272
- Norris, J. E., and Ryan, S. G. 1989, ApJ, 340, 739

- Norris, J. E., and Ryan, S. G. 1991, ApJ, 380, 403
- O'Connell, D. J. K. 1958, The Vatican Conference on Stellar Populations, (Amsterdam: North Holland)
- Olszewski, E. W., Schommer, R. A., Suntzeff, N. B., & Harris, H. C. 1991, AJ, 101, 515
- Oort, J. H. 1927, BAN, 3, 275
- Oort, J. H. 1927, BAN, 4, 79
- Oort, J. H. 1965, in Galactic Structure, eds. A. Blaauw & M. Schmidt (Univ. of Chicago Press: Chicago), p. 455
- Oort, J. H., & Plaut, L. 1975, AA, 41, 71
- Ortolani, S., 1990, ESO Messenger, 43, 23
- Ortolani, S., Barbuy, B., & Bica, E. 1990, A&A, 236, 362
- Ortolani, S., Barbuy, B., & Bica, E. 1992, ApJ, 408, L29
- Ortolani, S., Bica, E., & Barbuy, B. 1993, A&A, 267, 66
- Ortolani, S., Bica, E., & Barbuy, B. 1993, A&A, 273, 415
- Ortolani, S., Rich, R. M. 1993, in preparation
- Phillips, J. P., Martinez Roger, C., Sanchez Magro, C., & Lazaro Vilchez, C. 1986, AA, 161, 257
- Pagel, B. E. J. 1989, in "Evolutionary Phenomena in Galaxies", eds. J. E. Beckman and B. E. J. Pagel (Cambridge: Cambridge Univ Press), p. 201
- Peterson, C. J. 1986, PASP, 98, 610
- Peterson, C. J. & Latham, D. W. 1986, ApJ, 305, 645
- Pier, J. R. 1983, ApJS, 53, 791
- Pier, J. R. 1984, ApJ, 281, 261
- Plaskett, J. S. 1936, JRASC, 30, 153

- Plaut, L. 1971, AA, 8, 341
- Pottasch, S. R. 1992, A&AR, 4, 215
- Preston, G. W., Schectman, S. A., & Beers, T. C. 1991, ApJ, 375, 121
- Pritchett, C. 1983, AJ, 88, 1476
- Pryor, C. P., Latham, D. W., and Hazen, M. L. 1988, AJ 96, 123
- Pryor, C., & Meylan, G. 1993, in Proceedings of the Berkeley Workshop on Structure and Dynamics of Globular Clusters, eds. G. Meylan and G. Djorgovski, (ASP Conf. Series No. 50), p. 357
- Quinn, P. J., Hernquist, L., & Fullager, D. P. 1993, ApJ, 403, 74
- Racine, R., & Harris, W. E. 1989, AJ, 98, 1609
- Ratnatunga, K. U., & Freeman, K. C. 1990, AJ 97, 139
- Reed, R. C., Hesser, J. E., & Shawl, S. J. 1987, PASP, 100, 545
- Reid, M. J. 1989 in IAU Symp. No. 136, 'The Center of the Galaxy', ed. M. Morris, (Kluwer, Dordrecht), p. 37
- Renzini, A. 1992, in IAU Symp. 149 "The Stellar Populations of Galaxies", eds B. Barbuy & A. Renzini (Kluwer: Dordrecht), p. 325
- Renzini, A. 1993, in IAU Symp 153 Galactic Bulges, eds. H. Habing & H. DeJonghe (Dordrecht: Kluwer), in press
- Rich, R. M. 1988, AJ, 95, 828
- Rich, R. M. 1990, ApJ, 362, 604
- Rich, R. M. 1990, in "Bulges of Galaxies", eds B. Jarvis and D. Terndrup (ESO: Garching), p. 65
- Rich, R. M. 1992, in IAU Symp. 149 "The Stellar Populations of Galaxies", eds B. Barbuy & A. Renzini (Kluwer: Dordrecht), p. 39
- Rich, R. M. 1993, in Proceedings of the Santa Cruz Summer Workshop " The Globular Cluster-Galaxy Connection", eds J. Brodie and G. Smith, p. 287

- Rich, R. M. 1993, in IAU Symp. 153 Galactic Bulges, eds. H. Habing & H. DeJonghe (Dordrecht: Kluwer), in press
- Rich, R. M. 1993, in Galaxy Evolution: The Milky Way Perspective, ed. S. R. Majewski (ASP Conf. Series Vol. 49: ASP), p. 65
- Rich, R. M., & Mould, J. R. 1991, AJ, 101, 1286
- Rich, R. M., Mould, J. R. & Graham, J. 1993, AJ, in press
- Rich, R. M., & Whitford, A. E. 1984, PASP, 96, 794
- Richstone, J., and Tremaine, S. (1987) ApJ 327 82.
- Ried, M. J. 1993, ARA&A, 31, 345
- Rieke, G. H., & Lebofsky, M. J. 1985, ApJ, 288, 618
- Rieke, M. J. 1993, in Back to the Galaxy, AIP Conf. Proc. No. 278, eds. S. S. Holt & F. Verter (AIP: New York) p. 37
- Rieke, M. J. 1987, in Nearly Normal Galaxies, ed. S.M. Faber (New York : Springer Verlag), p. 90
- Rix, H.-W. 1993, PASP, 105, 999
- Rix, H.-W., & Rieke, M. J. 1993, ApJ, in press
- Robin, A. C., Creze, M., & Mohan, V. 1992, AA, 265, 32
- Rodgers, A. W., 1977, ApJ, 212, 117
- Rodgers, A. W., 1989, in Dynamics of Disk Galaxies, ed. B. Sundelius (Gottaborg: Sweden), p. 29
- Rose, J. A., & Agostinho, R. 1991, AJ, 101, 950
- Ruelas-Mayorga, R. A., & Teague, P. F. 1992, A&AS, 93, 61
- Ryan, S. G., & Norris, J. E. 1993, in ASP Conf. Series Vol. 49 Galaxy Evolution: The Milky Way Perspective, ed. S. R. Majewski (ASP), p. 103
- Saha, A., 1985, ApJ, 289, 310
- Sandage, A. 1990, J.R.A.S.Canada, 84, 70

- Sandage, A. 1986, AA, 161, 89
- Sandage, A., & Fouts, G. 1987, AJ, 93, 74
- Sandage, A., & Schwarzschild, M. 1952, ApJ, 116, 463
- Sandage, A., & Wallerstein, G. 1960, ApJ, 131, 598
- Sarajedini, A., & King, C. R. 1989, AJ, 98, 1624
- Sarajedini, A., & Norris, S. 1993, ApJS, in press
- Schuster, W., & Nissen, P. E. 1987, in *Stellar Evolution and Dynamics in the Outer Halo of the Galaxy*, eds. M. Azzopardi, & F. Matteucci (Garching: ESO), p. 141
- Searle, L., and Sargent, W. L. (1972) Ap.J. 173 25
- Searle, L., and Zinn, R. 1977, ApJ, 213, 368
- Searle, L., and Zinn, R. 1978, ApJ, 225, 357
- Sellwood, J. A. 1993, in *Back to the Galaxy*, AIP Conf. Proc. No. 278, eds. S. S. Holt & F. Verter (AIP: New York) p. 133
- Sellwood, J. 1993, in *IAU Symp. 153 Galactic Bulges*, eds. H. Habing & H. DeJonghe (Dordrecht: Kluwer), in press
- Shapley, H. 1918, ApJ, 48, 154
- Shapley, H. 1919, ApJ, 50, 107
- Sharpless, J., Walker, A., and Cropper, J. 1990, MNRAS 246, 54
- Shaw, M. A., & Gilmore, G. 1990, MNRAS 242, 59
- Simkin, S. M. 1971, AA, 31, 129
- Smith, V., & Plez, B. 1993 (private communication)
- Snedden, C., Kraft, R. P., Langer, G. E., Prosser, C. F., & Shetrone, M. D. 1993 (preprint)
- Sommer-Larsen, J. 1987, MNRAS, 227, 21P

- Spaenhauer, A., Jones, B. F., and Whitford, A. E. 1992, AJ 103, 297
- Spite, M., & Spite, F. 1985, ARA&A, 27, 279
- Sprayberry, D., Impey, C., & Bothun, G. 1993, preprint
- Statler, T. S. 1988, ApJ, 331, 71
- Stetson, P. B. 1987, PASP, 99, 191
- Straniero, O., & Chieffi, A., 1991, ApJS, 76, 525
- Suntzeff, N. B. 1993, in Proceedings of the Santa Cruz Summer Workshop "The Globular Cluster-Galaxy Connection", eds J. Brodie and G. Smith (ASP), p. 167
- Suntzeff, N. B., Schommer, R. A., Olszewski, E. W., & Walker, A. 1992, AJ, 104, 1743
- Suntzeff, N. B., Mateo, M., Olszewski, E. W., & Weller, W. 1992, AJ, 104, 1743
- Suntzeff, N. B., Mateo, M., Terndrup, D., Olszewski, E. W., Geisler, D., & Weller, W. 1993, ApJ, in press
- Suntzeff, N. B., et al. 1991, ApJ 367, 568
- Taam, R. E., Kraft, R. P., & Suntzeff, N. 1976, ApJ, 207, 201
- Taylor, B. J., Johnson, S. B., & Joner, M. D. 1987, AJ, 93, 1253
- Terndrup D. M. 1988, AJ, 96, 884
- Terndrup, D. M., in IAU Symp. 153 "Bulges of Galaxies", eds. H. Habing & H. DeJonghe, in press
- Terndrup, D. M., Blanco, V. M., Frogel, J. A. , and Whitford, A. E. 1990, ApJ 353, 494
- Terndrup, D. M., Frogel, J. A. , and Whitford, A. E. 1990, ApJ 357, 453
- Terndrup, D. M., Frogel, J. A. , and Whitford, A. E. 1991, ApJ 378, 742
- Terndrup, D. M., and Blanco, V. M. 1990, AJ 98, 843
- Terzan, A., & Ju, K. H. 1980, ESO Messenger, 20, 6

- Thielemann, F.-K., Hashimoto, M. & Nomoto, K. 1990, *ApJ*, 349, 222
- Thomas, P. 1989, *MNRAS* 238, 1319
- Tinsley, B. M., & Mould, J. E. 1976, *ApJ*, 203, 52
- Tonry, J., & Davis, M. 1979, *AJ*, 84, 1511
- Toomre, A. 1977, in *The Evolution of Galaxies and Their Stellar Populations*, eds. B. M. Tinsley & R. B. Larson (Yale Univ. Press: New Haven), p. 401
- Tremaine, S., Ostriker, J. P., & Spitzer, L. 1975, *ApJ*, 196, 407
- Tyson, N. D. 1991, PH.D. thesis, Columbia Univ.
- Tyson, N. D., in *Back to the Galaxy*, AIP Conf. Proc. No. 278, eds. S. S. Holt & F. Verter (AIP: New York) p. 141
- Tyson, N. D., & Rich, R. M. 1991, *ApJ*, 367, 547
- Udalski, A., Szymanski, M., Kaluzny, J., Kubiak, M., & Mateo, M. 1993, *Acta Astronomica*, 43, 69
- van Albada, T. S. 1982, *MNRAS* 201, 939
- van den Bergh, S. 1971, *AJ*, 76, 1082
- van den Bergh, S. 1993, *ApJ*, 411, 178
- van der Marel, R. P. 1991, *MNRAS* 248, 515
- VandenBerg, D. A., & Laskerides, P. G. 1987, *ApJS*, 64, 103
- VandenBerg, D. A., Bolte, M. & Stetson, P. B. 1990, *AJ*, 100, 445
- van der Veen, W., & Habing, H. J. 1990, *AA*, 231, 404
- Walker, A. R., & Mack, P. 1986, *MNRAS*, 220, 69
- Walker, A., and Terndrup, D. M. 1991, *ApJ*, 378, 119
- Webbink, R. F.. 1985, in *IAU Symp. 113 "Dynamics of Star Clusters"*, eds. J. Goodman and P. Hut (Dordrecht:Reidel), p. 550

- Weiland, J. L., et al. 1993, in *Back to the Galaxy*, AIP Conf. Proc. No. 278, eds. S. S. Holt & F. Verter (AIP: New York) p. 137
- Wheeler, J. C., Sneden, C., & Truran, J. W. 1989, *ARA&A*, 27, 279
- White, S. D. M. 1985, *ApJ*, 294, L99
- White, S. D. M. 1989, *MNRAS* 237, 51P
- Whitelock, P. A. 1993, in *IAU Symp. 153 "Bulges of Galaxies"*, eds. H. Habing & H. DeJonghe, in press
- Whitelock, P. A., Feast, M. W., & Catchpole, R. M. 1986, *MNRAS*, 222, 1
- Whitelock, P. A., Feast, M. W., & Catchpole, R. M. 1991, *MNRAS*, 248, 276
- Whitford, A. E. 1985, *PASP*, 97, 205
- Whitford, A. E., & Rich, R. M. 1983, *ApJ*, 274, 723
- Wielen, R. 1977, *A&A* 60, 263
- Wielen, R., 1974, in *Highlights of Astronomy*, ed. G. Contopoulos, (Reidel: Dordrecht), p. 395.
- Wyse, R. F. G., and Gilmore, G. 1992, *AJ*, 104, 144
- Wyse, R. F. G., and Gilmore, G. 1993, in *Proceedings of the UC Santa Cruz Summer Workshop "The Globular Cluster-Galaxy Connection"*, eds. J. Brodie and G. Smith, p. 727
- Wyse, R. F. G., and Gilmore, G. 1993, in *ASP Conf. Series Vol. 49 Galaxy Evolution: The Milky Way Perspective*, ed. S. R. Majewski (ASP), p. 209
- Wyse, R. F. G., & Gilmore, G. 1993, in *Back to the Galaxy*, AIP Conf. Proc. No. 278, eds. S. S. Holt & F. Verter (AIP: New York) p. 359
- Zaritsky, D., & Lo, K.-Y. 1986, *ApJ*, 303, 66
- Zinn, R. 1985, *ApJ*, 293, 424
- Zinn, R. 1990, *J.R.A.S. Canada*, 84, 89
- Zinn, R. 1993, in *Proceedings of the Santa Cruz Summer Workshop "The Globular Cluster-Galaxy Connection"*, eds J. Brodie and G. Smith, p. 38
- Zinn, R., & West, M. J. 1984, *ApJS*, 55, 45