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THE MORPHOLOGY, ENVIRONMENT AND INTERSTELLAR MEDIUM OF
EARLY-TYPE GALAXIES AS A MEANS FOR STUDYING THE EVOLUTION
OF GALAXIES OUTSIDE OF CLUSTERS

by

Julio Cesar Saucedo Morales

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

2000

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EARLY-TYPE GALAXIES AS A MEANS FOR STUDYING THE EVOLUTION
OF GALAXIES OUTSIDE OF CLUSTERS

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SIGNED: A handwritten signature in cursive script, appearing to read "John Puccio", is written over a horizontal line.

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DEDICATION

A la memoria de mis padres, que tanto deseaban verme concluir mi doctorado.
A mis hermanos y a toda la gran familia Saucedo-Morales-Samaniego-Ochoa. Y
desde luego, con todo el amor de este mundo para Maria, Mayita y Julito.

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ABSTRACT

The main goal of this thesis is to study the properties of isolated early-type galaxies with the hope of learning about their formation and evolution. With this goal in mind, B and I optical, and K_s near infrared images of 4 different samples of early-type galaxies in contrasting galactic density environments have been secured with the Steward Observatory 90 inch and 61 inch telescopes. The 4 early-type galaxy samples consist of: a sample extracted from the Catalog of Isolated Galaxies of Karachentseva, a sample of isolated galaxies previously studied by Fasano and Bonoli, a sample of galaxies from the Hickson Compact Groups Catalog, and a sample of galaxies with detected ISM's. This data set is used to examine whether differences in the galactic environment are related to differences in key properties of early-type galaxies.

Multi-color surface photometry analysis is performed on the 4 samples, and the results are used in several contexts. For most of the galaxies in the Karachentseva sample surface photometry is reported for the first time. Likewise, K_s data for most of the objects in this thesis have never been reported. The light profile of the galaxies are fitted with Sersic profile functions. In agreement with other investigations, it is found that the Sersic parameter n is primarily dependent on the galaxy size, and does not seem to be strongly dependent on properties such as environment or ISM content. The $(B - I)$ color index, ellipticity, position angle, and third and fourth-order Fourier coefficients are derived from the surface photometry. It is confirmed that the third-order coefficients signal the presence of dust, and that the coefficient of the $\cos(4\theta)$ gives structural information of the galaxies. Furthermore, the subtraction of model ellipticals has revealed peculiarities

in the morphology, such as disks, spiral arms, dust lanes, multiple nuclei, etc.

The largest and most relevant sample in this investigation consists of 39 galaxies, and it contains $\sim 25\%$ of the galaxies classified as ellipticals in the Karachentseva catalog. Only approximately one half of the galaxies classified as ellipticals in that catalog appear to be correctly classified, a result which may imply a reduction of the percentage of ellipticals in the Karachentseva catalog to $\sim 6\%$ of the total population of Isolated Galaxies. A significant number of merger candidates has also been found among the isolated galaxies. It is argued that the fraction of merger candidates to isolated ellipticals can be used to constrain models for the evolution of compact groups into isolated galaxies. The results of CO(1-0) millimetric wavelength observations taken at the NRAO 12 M telescope, as well as submillimeter continuum emission from dust at the SMT are also presented.

CHAPTER 1

INTRODUCTION

1.1. Historical Background

This thesis is mainly concerned with the study of an important class of galaxies known as “early-type galaxies”. Due to the nature of this study, it is convenient to start by giving some background information of what is known about these objects within the general context of extragalactic research. The words “Galaxy” and “Milky Way” have their origin in Greek and Latin mythology. These names were given to the band of light in the sky, which can best be seen during moonless nights in the summer and winter skys. Undoubtedly the “milky” appearance of our galaxy must have caused awe to the Greeks and to other great cultures of the past, but a real scientific understanding was still far in the future. The first serious astronomical investigations of our galaxy can be traced back to the beginning of the 17th century. At that time, Galileo, introduced to astronomical research the use of the recently invented telescope. During a very short period of time, Galileo made an impressive number of astronomical discoveries, among them was his finding that the “milky” appearance of the Milky Way is actually the result of an immense number of stars, which the naked eye is unable to resolve. Thus, he was very likely

the first human to have at least a rough idea of the true nature and dimensions of the Galaxy.

Later on, the construction of larger telescopes in the 18th and 19th century, mainly by W. Herschel, and W. Parsons, made possible the discovery of a large number of “diffuse Nebulae”. The discovery of the “spiral nebulae” by W. Parsons was a particularly important breakthrough in extragalactic research, but the nature of these objects remained controversial for a very long time. It was not clear whether the spirals were small and nearby, contained within the Milky Way, or large and distant “island universes”. This controversy reached its final crisis in the “Great Debate” between Harlow Shapley and Heber Curtis, which took place on April 26, 1920. The controversy was finally settled by Edwin Hubble in 1923 in favor of the island universes model, by measuring the distance to the Andromeda galaxy (M31) with a method developed by Henrietta Leavitt to measure distances to Cepheid variables. Taking advantage of the great aperture of the 100 inch Hooker Telescope at Mt. Wilson, Hubble was able to resolve cepheids in Andromeda, and using the period-luminosity relation calibrated by Shapley, found this distance to be about 10 times the size of our own galaxy (which had been previously measured by Harlow Shapley), thus showing that the Andromeda galaxy was clearly outside of the Milky Way.

After establishing the nature of galaxies, Hubble made an even more exciting discovery. In 1915, Vesto Slipher, working at the Lowell Observatory had discovered that the spectral lines of the galaxies he had observed were redshifted. According to the Doppler effect, this would mean that these galaxies were moving away from us. Hubble decided to pursue these investigations. He estimated the distances to the galaxies with measured redshift, and found a linear relationship between the

receding velocity and the distance to the galaxies. This relationship now known as Hubble's Law, was the first evidence that the universe is expanding. With these two discoveries made by Hubble, galaxies achieved the prominent place they now occupy in astronomical research.

1.2. Morphological Properties of Galaxies

The detailed images of galaxies which Hubble observed at Mt. Wilson, gave him the opportunity to develop the morphological classification of galaxies that bears his name. He observed that galaxies could be classified as either: ellipticals, lenticulars (S0 galaxies), spirals, or irregulars. According to his interpretation of the observations, he thought there was an evolutionary sequence from "early" to "late" type galaxies. He regarded ellipticals and S0s as "early-types", and spirals and irregulars as "late-types". Although the evolutionary sequence he proposed has long been rejected, the terminology he used is universally used in the astronomical jargon.

Perhaps the success of the Hubble classification is due to the striking difference between ellipticals and spirals. Indeed, the morphology of galaxies can be associated with a long list of physical characteristics. Besides their obvious differences in their shapes, ellipticals differ from spirals in the properties of their interstellar medium: in their star formation histories; in their stellar populations; in their stellar motions; in the galactic environment in which they live; etc.

1.3. Morphology, Environment and the Formation of Galaxies

Although all the properties of galaxies are important in their own right, those related to the morphology, the environment and the ISM content will occupy

most of the attention of this work. For a long time it has been known that most early-types reside close to the centers of clusters or in galaxy groups, and that only a fraction of them are in the field. In contrast, the majority of spirals lie in the field or in the outskirts of clusters, and almost never close to their centers. These statistical results clearly suggest that the explanation of the contrasting behaviors between spirals and early-type galaxies must be related to the question of how they form and evolve in different environments. Despite several theoretical efforts, however, there is still no universally accepted picture capable of explaining these differences; although several possible explanations have been advanced. Two possible scenarios for the formation mechanism of early-type galaxies have dominated the field in the last two decades. The dissipative collapse model, which is thought to produce most of the stars in a major burst during the collapse, was proposed by Larson (1975), and was later extended by Carlberg (1984). The other formation model is based on the merging hypothesis, proposed by Toomre and Toomre (1972), and Toomre (1977). Several objections have been raised to the dissipative collapse model. Among them is the fact that the tremendous bursts of star formation that are expected to occur according to this model have never been observed in any galaxy. For these reasons, the alternative mechanism, merging, is thought to be the most important player as a formation mechanism of early-type galaxies. The merging hypothesis also has the additional appeal of being the most natural mechanism for making galaxies according to a bottom-up hierarchical model of structure formation. In some recent versions of this model (Kauffmann 1996), the present population of galaxies in clusters is thought to have undergone merging processes at large redshift, while the galaxies were still in the field. Subsequently the galaxies assembled to form the clusters we see today (Kauffmann 1996). Several other mechanisms for the formation of early-types in

clusters have also been proposed. One of them is known as “galaxy harassment” (Moore et al. 1996, and Moore et al. 1998), which consists of frequent high speed close encounters (which should be common in clusters). But these, as well as a few other proposed mechanisms for the formation of early-types, are very recent and many of the details still need to be worked out.

1.4. Early-Type Galaxies: The last 20 years

Until the mid 1970s, early-type galaxies were generally regarded as extremely boring objects, devoid of ISM, incapable of forming new stars, and basically in the process of simply dying at very slow rates due to the aging of their stars. Then came the results of the far infrared astronomical satellite IRAS, which found that a significant fraction of early-type galaxies contain dust (Jura et al. 1987; Knapp et al. 1989). Likewise, the Einstein, ROSAT, and other X-ray satellites reported enormous amounts of hot coronal gas in several elliptical galaxies (Forman et al. 1985).

From the analysis of ground based observations, Bertola and Cappaccioli (1975), observed that the rotational velocity of ellipticals was too small to account for the degree of flatness found in these galaxies. It was then realized that their shapes could actually be explained by the large velocity dispersion of their stellar systems. This result, and the observation of isophotal twisting in ellipticals, gave rise to the triaxial models developed by Binney (1978). Furthermore, significant correlations were found among a wide range of properties of elliptical galaxies (Fundamental Plane), the most famous being the Faber-Jackson relation, which relates the luminosity with the velocity dispersion (Faber & Jackson 1976).

It was also found that most ellipticals become bluer with increasing radius

(Sandage & Visvanathan 1978, Peletier et al. 1990, and many others). Such color gradients were soon interpreted as due to metallicity gradients (although some investigators have suggested that variables such as age and dust may also play a role in their interpretation). More direct metallicity gradients have also been found by measuring the strength of the Mg2 line (Peletier 1989, and Davies et al. 1993).

Surface photometry studies have shown that ellipticals are not perfect, but present deviations or residuals of the order of 1% in their isophotes (Lauer 1985). Such isophote residuals usually signal the presence of weak stellar disks, dust, merging processes, radio power, x-ray luminosity (Bender et al. 1989), etc. For this reason, surface photometry analysis can be a very powerful technique to study the properties of early-type galaxies.

Finally, radio astronomy has also provided significant new information on the interstellar medium and other properties of early-type galaxies. A growing number of these galaxies have claims of neutral hydrogen (H I) detections at the 21-cm transition (Knapp et al. 1987, Huchtmeier 1994). On the other hand, millimeter and submillimeter studies have made it possible to detect the molecular gas as well as the dust component of the ISM. The molecular gas has been obtained through the application of molecular spectroscopy to the study of the lines CO(1-0) and CO(2-1) (Lees et al. 1991, Wiklind et al. 1995). The dust component has been obtained from ground observations of the thermal submillimeter continuum combined with far-infrared telescopes in space (Fich and Hodge 1990).

1.5. Goals of this Thesis

The goals of this project have evolved considerably from those that were originally planned. This work started with the goal of answering the following question. Are

there significant differences in the ISM content between isolated and high galactic density early-type galaxies? In other words, the main interest was focused in learning about the intrinsic versus extrinsic properties in the evolution of the ISM in early-type galaxies. Assuming that early-type galaxies follow a simple picture of passive evolution, it was expected that perhaps isolated early-type galaxies would be able to retain their ISM more efficiently than those in clusters. Care was taken in selecting a sample of very isolated galaxies, not subject to the ram pressure in clusters, and with no obvious companions to affect their evolution. It was then decided that the galaxies with $B_T < 15$ classified as early-type in the Catalog of Isolated Galaxies (Karachentseva 1973) would be appropriate for this study. For a more complete understanding of the ISM in these galaxies, it was decided to study the sample at a wide range of wavelengths. The project began by searching for gas and dust, at millimeter and sub-millimeter wavelengths. From the low detection rates found for a small fraction of the sample, it became clear that for most of the galaxies it would only be possible to obtain upper limits for the masses of gas and dust of these galaxies. For this reason, it was decided to concentrate the effort on an imaging program to be carried out at visible and infrared wavelengths. B and I optical images were taken at the Steward Observatory 90 inch telescope, and K_s infrared images at the Steward Observatory 90 inch and 61 inch telescopes. The B , I , K_s bands were chosen, in order to have a large spread in the wavelength baselines for the study of color properties. The K_s infrared observations were deemed important, to diminish the effect of reddening and extinction due to dust. This has enabled to obtain a better knowledge of the presence of dust, the mass distribution and morphology of the galaxies. The findings from the imaging study were somewhat surprising. The number of normal looking early-types found was very low, which indicates that less than 10% among the most isolated galaxies

are true early-types. Furthermore, a significant number of objects with merger signatures was also found, which indicates that among the most isolated galaxies the ratio of merger candidates to bona-fide early-types is significant. These results suggested that perhaps it would be possible to constrain models for the evolution of galaxies outside of clusters.

The low number of bona fide early types in the Karachentseva sample prompted us to study “isolated” early-types that are not in the Karachentseva catalog. This led us to study the sample of Fasano and Bonoli (1989). In order to compare the properties of isolated early-types with those in high density environments, a sample including some of the brightest early-types in the Hickson Catalog of Compact Groups (Hickson 1982) observable from the northern hemisphere is also studied. Finally, a sample of early-type galaxies with detected ISM is also included.

Some of the studies done with the imaging data are the following. Surface photometry analysis is used, to compare the parameters that result for the 4 different samples. It would be interesting to find out if isolated early-types present less perturbed isophotes, as should probably be expected, if merging processes do not play an important role in their formation. Likewise, it would be interesting to know if the isophotal shifts present any significant difference. According to the study of Fasano and Bonoli (1989), isophotal shifts seem to occur at the same frequency regardless of the environment. With the present, more isolated sample this question can be addressed again. The color gradients that result from the isolated sample will be compared with those of the compact groups sample, as well as with those which are typical among the cluster ellipticals. Although results for the latter abound in the literature, no systematic work has been done for early-types in isolated environments. From a physical point of view, it would

appear that the evolution of these objects should have been significantly different in the different environments. For instance, the ISM in isolated galaxies might depend only on internal mechanisms, i.e. no input or output of ISM would be expected due to the presence of other galaxies. It is possible to establish the presence of disks, spiral arms, dust lanes, etc., by simply subtracting elliptical models from the light distribution of the galaxies. This technique will be employed to extract statistical information about the galaxies under study, which should be very valuable in constraining models for galaxy evolution. It should also be interesting to see whether we can find dust lanes, or any trace of dust distributions among the isolated early-types. Since dust lanes have always been thought to be due to galaxy interactions, they would be hard to explain for non-interacting early-type galaxies.

As was briefly mentioned above, the long held view that early-type galaxies do not possess significant amounts of interstellar medium (ISM), has been challenged by the detection of several components of the ISM at different wavelengths in these galaxies. This thesis studies whether these galaxies are really normal early-type, and not misclassified spirals, for instance. With this purpose in mind, images have been taken of a significant number of early-type galaxies for which strong cases of ISM detections have been claimed. The difficulties encountered in classification are well appreciated, and good discussions about this problem have been published by several authors (Roberts et al. 1991, Knapp et al. 1989, Bregman et al. 1992, etc.). Unfortunately, except for relatively bright nearby galaxies, there is still a great deal of uncertainty in the morphological classification of the so-called early-type galaxies. Aside from the concerns related to the gross morphology, it would also be very interesting to know if these galaxies possess structural features indicative of merging, dust lanes, or peculiarities of any other kind. These data will also be used as for the interpretation of the presence of dust in the samples with different

environments. The ISM detected sample, in combination with the infrared K_s data has been particularly useful in this regard.

1.6. Outline of the Thesis

Chapter 2 explains how the 4 different samples of galaxies studied in this thesis were selected, and relevant information for each galaxy is presented. A clear description of the samples is important, to be able to see if effects such as the environment, ISM content, etc. play a role in the interpretation of the properties of galaxies. In Chapter 3, the surface photometry analysis of the B and I CCD data is presented. Likewise, the results for the K_s data are presented in Chapter 4. Chapter 5 briefly describes some of the current ideas about the evolution of galaxy groups through merger processes. That introduction provides a framework for the discussion of the results of the statistical study of the morphology of early-type galaxies in the Karachentseva sample. The results for the surface photometry study at optical and infrared wavelengths are also discussed on Chapter 5. They are presented in two parts. First, the light profile of the galaxies is studied using the Sersic profile formalism. Correlations among the Sersic parameters as well as correlations of these parameters with galaxy properties are discussed. Second, the study of the properties of galaxies that are directly extracted from the surface photometry analysis. Color gradients, isophotal shifts, structural properties, as well as dust are considered. The comparison of the third and fourth order terms in the Fourier expansion obtained at different wavelengths is treated at length. Chapter 6 starts with a review of the recent history of detections of the different components of the ISM in early-type galaxies. These components include: dust, molecular gas, 21-cm neutral hydrogen observations, ionized gas, and the hot component from x-ray observations. The results of the attempts made in this work to detect the

dust continuum emission at the Heinrich Hertz submillimeter telescope, as well as the CO(1-0) observations done at the NRAO 12 meter telescope at Kitt Peak are also presented. Optical images of a fair number of the northern hemisphere early-type galaxies for which significant ISM components have been found are also presented. With these data it is possible to extract statistical results about the morphology of these objects. In chapter 7, a summary of the main contributions of this thesis will be presented.

CHAPTER 2

SAMPLES OF GALAXIES

2.1. General Selection Criteria

One of the primary objectives of this thesis is to study whether differences in the environment are responsible for differences in the properties of early-type galaxies. With this aim, a program of observations of galaxies in contrasting environments has been carried out. This chapter describes how the galaxy samples were chosen. Overall, four galaxy samples are considered. To study the low galactic density environments a sample of isolated galaxies extracted from the Catalog of Isolated Galaxies (KIG) of Karachentseva (1973) has been selected. A second sample of relatively isolated galaxies was taken from a selection of isolated early-type galaxies made by Fasano and Bonoli (1989). A sample of galaxies from the Compact Groups of Galaxies by Hickson (1982) was chosen to study the high galactic density environments. Finally, a sample of isolated early-type galaxies in diverse environments, known to contain ISMs was also included, to study the possible connection between the environment and the presence of an ISM. No specific sample of early-type galaxies in clusters (which is the most common environment for these galaxies) has been selected for this study. However, cluster early-types

have been extensively studied by several investigators, and in fact, most of what is known about the properties of early-type galaxies has been extracted from those studies. Some of the results from this work will be compared with those for cluster early-types from the studies by Caon et al. (1993), Goudfroiij (1994), and Graham et al. (1996).

In order to have meaningful statistical results, a fair number of galaxies for each sample had to be included. However, in order to obtain sufficiently deep images to be able to do detailed work of relatively faint galaxies ($B_T \sim 15$) for morphological and multicolor surface photometry studies, a compromise on the number of galaxies in each sample had to be made. These considerations have led us to give preference to the brightest galaxies within each sample. Further restrictions on the galaxies were to consider only galaxies with (galactic latitudes outside the Galaxy disk) $|b| > 20^\circ$ that are observable from the northern hemisphere. Overall 76 galaxies have been studied. These include: 39 galaxies from the KIG, 10 galaxies from the Fasano and Bonoli sample (one of the galaxies is also in the KIG), 11 early-types that are members of Hickson compact groups of galaxies, and 18 galaxies among the early-type galaxies with detected interstellar medium (two overlap with the KIG sample).

Several properties of the galaxies studied here were obtained from the NASA Extragalactic Database (NED), or from the Lyon Meudon Extragalactic Database (LEDa, Paturel et al. in 1989). Both databases contain updated information on all the galaxies considered in this study. The tabular format of LEDa was found to be convenient for calculating the projected distances to the nearest neighbor galaxies in the catalog.

2.2. Isolated Galaxies from the Karachentseva Catalog

One of the early motivations for this thesis came after reading a sequence of papers by Haynes and Giovanelli. The first of these (Haynes and Giovanelli 1980) reported significant HI detections for all the isolated early-type galaxies from the Karachentseva sample they had observed up to that time. The results from the larger sample (Haynes and Giovanelli 1984), however, did not follow the trend of detections of the first paper. It was not clear, whether the discrepant results were simply due to morphological misclassification, or to some characteristic property of the isolated early-type galaxies. These puzzling results indicated that early-type galaxies in isolation were poorly understood, and that it would be interesting to study them in more detail.

The KIG catalog was constructed by visual inspection of the Palomar Sky Survey plates by Karachentseva (1973). She searched for the more isolated galaxies in the Catalog of Galaxies and Clusters of Galaxies of Zwicky et al. (1960-1968). The KIG consists of 1052 isolated galaxies of diverse morphology with $DEC > -3^\circ$, $m < 15.7$ mag and galactic latitude $|b| > 20^\circ$. Under Karachentseva's criteria for "isolation", an isolated galaxy of angular diameter d should be separated by more than $20 \times d$ from its nearest "significant" galactic neighbor, where significant galaxies are those large enough to be in the range between $d/4$ and $4 \times d$ in angular diameter. Since the Karachentseva's isolation criteria are purely based on angular quantities, without taking into consideration the redshift information, the degree of spatial isolation of the galaxies would be unknown. For instance, two galaxies at very low redshift (i.e. close to the Milky Way) could have a large angular separation, and yet only have a modest projected distance between them. For this reason, using redshift information now available for many of these galaxies (4 of

the galaxies in our list do not have a measured redshift), the projected distances to their nearest neighbor galaxies have been calculated in this work to assess the degree of isolation of the sample of KIG galaxies.

It is important to emphasize, that the KIG is not a complete sample of galaxies in either absolute or apparent magnitude. Using magnitudes and redshifts for 695 galaxies in the KIG (obtained from the LEDA catalog), the number of galaxies that exceed L/L^* has been calculated. For this calculation a value of -20.6 has been chosen for the blue absolute luminosity that corresponds to an L^* galaxy. The values that result for this empirical distribution are presented as points in Fig. 2.1. Following Mihalas and Binney (1981), assuming that the galaxies obey the Schechter luminosity function, the total number of galaxies in a given volume whose luminosity exceeds L is given by

$$N(> L) = N_0 \Gamma(\alpha + 1, L/L^*)$$

The incomplete gamma function can also be written

$$\Gamma(\alpha + 1, x) = [\Gamma(\alpha + 2)Q(\alpha + 2, x) - x^{\alpha+1}e^{-x}]/\alpha.$$

The complete gamma function $\Gamma(\alpha + 2)$ as well as incomplete gamma function $Q(\alpha + 2, x)$ have been calculated using routines from Numerical Recipes in Fortran (1992). The continuous curve at the top panel of Fig. 2.1 gives the number of galaxies expected for $\alpha = -1.5$ (with $N_0 = 700$), whereas the dashed line corresponds to $\alpha = -1.25$ (with $N_0 = 800$). These curves fit the data for $L > 0.6L^*$, but for galaxies with luminosities fainter than $0.6L^*$, the sample becomes increasingly incomplete. For $L = 0.1L^*$ only 10% of the galaxies are seen for the case $\alpha = -1.25$.

The KIG is not just incomplete, but it is also not homogeneous in space. The histogram at the bottom panel of Fig. 2.1 presents the redshift distribution of the

galaxies in the KIG (using the data for the 695 KIG galaxies with known redshift in LEDA). The dot-dashed curve has been taken from a study of the redshift distribution of the KIG by Haynes and Giovanelli (1983). This smooth curve represents the distribution for a sample of homogeneously distributed galaxies with the same apparent magnitude distribution. The two prominent structures at 1500 km s^{-1} and at $+5000 \text{ km s}^{-1}$ have been identified by Haynes and Giovanelli (1983) as due to the Local Supercluster, and to the Pisces-Perseus Supercluster respectively. According to them, the KIG galaxies lie at the lowest density regions of these superclusters. They also note that “such isolated galaxies have existed for virtually their entire lifetimes on the distant peripheries of supercluster systems and hence may represent a population untouched by environmental influences on their evolution”. As far as this work is concerned, even if these galaxies are not truly isolated, the large projected distances to their nearest neighbors makes them attractive to study galaxies in low galactic density environments far from the influence of clusters or from any obvious companion.

The original plan was to have only one sample for the isolated early-types, with all of these galaxies extracted from the KIG. However, even though most of the galaxies in the KIG appear to be isolated (at least in the sense discussed above), it was soon found that there were serious problems with their morphological classifications. Several of these galaxies turned out to be spirals, or to have perturbed morphologies, and they were initially excluded from the sample. Furthermore, only a small percentage of the early-type galaxies in the KIG catalog were bright enough (within the constraints of telescope time allocation) for the detailed multicolor surface photometry required for this work. The combination of these two factors left only a handful of galaxies from the KIG catalog suitable for the study of isolated early-type galaxies. For this reason, in order to have a larger

number of isolated early-type galaxies, it was decided to include isolated galaxies which are not in the KIG catalog.

It was only after discarding a considerable number of KIG galaxies that the seriousness of the misclassification problem among the KIG galaxies was realized. At that point, the statistical results of the morphology of isolated galaxies began to be investigated. The observed galaxies from the Karachentseva sample, including those originally discarded, are listed on Table 2.1, where some relevant information is also provided.

As far as this work is concerned, the most important property of the KIG catalog is the uniformity in the criteria with which the isolated galaxies were selected and classified by Karachentseva. These characteristics of the KIG justify its use in the search for statistical properties of isolated early-type galaxies.

2.3. The Fasano and Bonoli Sample

Most of the rest of the galaxies selected for the isolated sample come from the list of isolated early-type galaxies studied by Fasano and Bonoli (1989). They were interested in studying the intrinsic isophotal twisting of early-type galaxies. With the purpose of minimizing the distortions produced by the presence of companions, they decided to study a sample of isolated early-type galaxies. The selection criteria adopted by Fasano & Bonoli were the following. They chose galaxies classified as ellipticals in the UGC Catalog (Nilson 1973) which are not members of any Abell cluster (Abell 1958), and do not have any companion explicitly mentioned in the UGC catalog (they did not specify any threshold for angular separation or distance). To obtain good quality profiles, they further restricted their selection to relatively large galaxies with semi-major axis between 0.8 and 1.2 arc minutes.

The decision to study galaxies from the Fasano & Bonoli sample for this work, was taken after finding only a low percentage of “bona fide” elliptical galaxies in the KIG catalog. The Fasano & Bonoli sample provides a fairly clean sample of ellipticals which is appropriate for studies of surface photometry, etc. There are, however, important differences between the KIG catalog of Karachentseva and the Fasano & Bonoli samples that need to be recognized. The first difference is, that the Fasano & Bonoli galaxies were extracted from the UGC Catalog, and the lower limit on the semi-major axis criterion imposed by Fasano & Bonoli, makes these objects less prone to morphological misclassification than the galaxies in the KIG. Another important difference between the two isolated samples, is that Fasano and Bonoli did not apply any quantitative criterion of isolation. In fact, their galaxies (except for a few cases) are not as isolated as those in the KIG. The degree of isolation was of no serious concern for the purposes of Fasano & Bonoli’s work, because they were just interested in avoiding the effect of distortions on the light distribution of a galaxy due to the presence of another galaxy along the line of sight. These differences in the samples show why the results of the KIG sample are the ones that will be relevant to study properties of isolated elliptical galaxies. The Fasano & Bonoli sample constitutes a control sample of relatively featureless galaxies. Another reason for studying the Fasano & Bonoli sample is that a direct comparison of the results of the surface photometry analysis between their work and the present study can be made. This is important since only a few of the galaxies reported in this thesis have previously published surface photometry.

The entire list of elliptical galaxies studied by Fasano & Bonoli consists of 43 objects. Two of those galaxies are also in the KIG. For this work, we excluded all the galaxies with $B_T > 15$, those for which Fasano & Bonoli found companions, as well as those with stars in the foreground of the galaxies. The objects selected for

this work include 10 of their objects, and they are listed on Table 2.2.

2.4. Galaxies in Hickson Compact Groups

The interest in studying early-types in compact groups is two-fold. First, these galaxies lie at very high galactic densities and should be good targets for comparing their properties with those of isolated galaxies, which are at the opposite extreme in galactic densities. The second reason has to do with a possible connection that may exist in the evolutionary history of galaxies in these two kinds of environments. In some theories of galaxy evolution, compact groups are thought to be the progenitors of the isolated early-type galaxies. Indeed, if the merger hypothesis is valid, it is expected that at least some (depending on the crossing time and the mass distribution of the group) isolated compact groups have life-times shorter than a Hubble time, and that they will eventually merge to become isolated galaxies. By comparing the properties of galaxies in compact groups with those of isolated early-types, it might be possible to find clues about the connection between the galaxies in these two contrasting environments.

There are several catalogs of compact groups of galaxies: Shakhbazyan (1973), Petrosyan (1974), Rose (1977), Petrosyan (1978), and Hickson (1982). Galaxies from the Atlas of Compact Groups of Galaxies by Hickson (HCG) were selected for this work, due to the high rate of success it has had in finding true, physically associated groups. Among the 100 compact groups (both hemispheres) in the HCG, groups with firmly established membership (i.e. with concordant redshifts) that contain relatively bright early-type galaxies ($B_T < 15$) in the northern hemisphere were selected. The list of galaxies for this sample is given in Table 2.3. It includes 12 Hickson groups, and a total of ~ 20 early-type galaxies.

2.5. Sample of Early-Type Galaxies with Detected ISMs

One of the most significant developments in the study of early-type galaxies in recent years, has been the claim that a high percentage of them contain significant ISMs. Several studies have concentrated on detecting the cold ISM of “early-type” galaxies. However, none of those studies report optical or infrared images to verify that the galaxies really correspond to typical early-types. With this study, such claims will be analyzed. This will be done by checking whether the morphology of ISM detected galaxies really correspond to those of early-type galaxies. It would also be interesting to determine what kind of properties early-types with detected ISM typically have.

Aside from this, it would be useful to have a sample of galaxies with detected ISM, that one could use for comparison with the galaxies in the other samples. This could be an important step towards learning whether galaxies in different environments have different ISM content and properties. The ISM detected sample of early type galaxies has been drawn from some of the strongest cases of cold ISM detections from the northern hemisphere. It includes dust continuum emission detections (Fich & Hodge 1993, Wiklind & Henkel 1995); molecular CO(1-0) and CO(2-1) emission detections (Wiklind, Combes and Henkel 1995) and neutral hydrogen emission detections (Huchtmeier, Sage and Henkel 1995). The total sample consists of 19 galaxies. Two of these overlap with the KIG sample (KIG 83 = UGC 1503, KIG 841 = NGC 6524). It is important to point out, that this particular sample was not selected in terms of the environment. In fact, after finding the distance to their nearest neighbors, it is easy to see that the galaxies chosen come from a wide range of environments. A good fraction of these galaxies are relatively isolated, while others are in compact groups or in clusters. The list

of the galaxies selected for this sample is given in Table 2.4.

2.6. Determination of the Environment of Galaxies

Since the isolation of the galaxies in both the Karachentseva and the Fasano and Bonoli samples were determined purely on the basis of the angular separation, it is important to determine the projected distances in megaparsecs to the nearest neighbors for all the galaxies in the samples. Also, although the information about the environment is known for the galaxies in the Hickson compact groups, it is not available for the galaxies in the sample with detected ISM. For all the galaxies, the information on the galactic environment is relevant for a more complete discussion of their properties.

For the galaxies with known velocity, the projected distances to their nearest galactic neighbors is given by $\delta\theta \times v/H_0$, where $\delta\theta$ is the angular separation to the nearest neighbor, and v is the recessional velocity of the galaxy under study. The information on galaxies needed for these calculations has been extracted from the LEDA database. The procedure used is very straightforward. The angular separation between the sample galaxy and all the galaxies listed in the LEDA catalog which are contained in a large square in RA and DEC space (The size of the square is $10^\circ \times 10^\circ$ and it is centered on the sample galaxy) is determined. The analytical expression for the angular separation between a sample galaxy s and galaxy i is given by

$$\delta\theta_{si} = \cos^{-1}(\sin(\delta_s)\sin(\delta_i) + \cos(\delta_s)\cos(\delta_i)\cos(\alpha_s - \alpha_i)),$$

where (α_s, δ_s) are the right ascension and declination of the sample galaxy expressed in radians. The previous expression for $\delta\theta_{si}$, however, turns out to be

problematic for small angular separations, due to the computation of trigonometric functions for very small angles. In such cases (for angles smaller than 10 arc minutes), the following approximation gives more reliable results

$$\delta\theta_{si} = (((\alpha_s - \alpha_i)\cos((\delta_i + \delta_s)/2))^2 + (\delta_i - \delta_s)^2)^{1/2}$$

The projected distances are then calculated for all the galaxies with known velocities. As a final step, the galaxies are sorted according to their distance from the nearest to the farthest. The projected distances to the nearest neighbor galaxy (listed in LEDA) in megaparsecs are given in column 8 of Tables 2.1 - 2.4. These tables also include: the coordinates, the total blue apparent magnitude B_T , the velocity, the distance to the galaxy in megaparsecs, the projected angular separation of the nearest neighbor in arc minutes, and the morphological type code.

TABLE 2.1
SAMPLE OF ISOLATED EARLY-TYPE GALAXIES FROM THE CATALOG OF ISOLATED GALAXIES OF KARACHENTSEVA

Galaxy	R.A. (1950)	DEC (1950)	B_T [mag]	VEL [km/s]	Dist. Mpc ^b	$\theta(NN)$ ['] ^c	Dist(NN) Mpc	Type ^d
KIG 0074	01 54 36.0	+28 20 02	15.0	10350	138.0	1.66	0.07	-2.8
KIG 0083	01 58 24.2	+33 05 19	14.4	5085	67.8	30.8	0.61	-4.8
KIG 0089	02 05 40.5	+10 45 32	11.7	1720	22.9	256.0	1.71	-4.8
KIG 0120	02 51 24.0	+06 03 00	15.5	6701	101.3	5.3	0.16	+3.8
KIG 0128	03 28 48.9	+14 12 33	14.1	6594	87.9	73.4	1.88	-1.9
KIG 0179	07 07 56.2	+47 01 09	15.5	5813	77.5	60.4	1.36	-2.8
KIG 0248	08 21 23.5	+17 29 40	15.2	11055	147.4	157.6	6.76	-2.8
KIG 0303	09 04 59.9	+03 35 47	13.0	3827	51.0	60.6	0.90	-1.9
KIG 0308	09 06 43.4	+18 49 29	14.7	1129	15.0	128.2	0.24	-2.8
KIG 0358	09 37 40.5	+15 08 58	13.3	3821	50.9	96.0	1.42	-4.8
KIG 0393	10 00 22.2	+59 40 43	14.8	2604	34.7	40.5	0.41	-3.2
KIG 0396	10 00 59.8	+60 21 00	14.2	3065	40.9	40.5	0.48	-3.2
KIG 0437	10 41 18.0	+53 02 00	14.8	7568	100.9	91.7	2.69	-3.2
KIG 0443	10 44 50.6	+06 18 38	14.3	5837	77.8	64.5	1.46	+1.3
KIG 0467	11 06 31.3	+36 17 32	14.4	6390	85.2	45.4	1.13	-1.8
KIG 0501	11 46 01.6	+32 54 50	15.4	6999	93.3	41.8	1.13	-0.3
KIG 0503	11 47 35.1	+42 21 12	14.5	1033	13.8	100.7	0.40	-2.8
KIG 0505	11 49 22.2	-02 21 54	15.1	3865	51.5	42.1	0.51	+1.9
KIG 0511	11 52 31.0	+01 59 48	15.1	1308	17.4	30.1	0.15	-3.0
KIG 0537	12 32 32.3	+26 03 18	15.8	9039	120.5	32.3	1.01	+1.4
KIG 0555	12 50 43.5	+25 32 58	15.8	1130	14.1	35.4	0.15	+1.4
KIG 0633	15 08 12.0	+67 23 00	13.5	4298	57.3	20.8	0.35	-4.9
KIG 0697	15 40 01.8	+02 10 20	14.9	3567	47.6	53.6	0.74	-1.9
KIG 0705	15 46 53.2	+37 21 28	15.3	11935	159.2	53.6	2.48	-2.8
KIG 0714	15 54 17.0	+49 40 45	15.4	5707	76.1	58.7	1.30	+4.4
KIG 0721	16 06 00.0	+39 19 36	15.3	^a	...	...	...	-2.8
KIG 0732	16 15 38.6	+53 07 40	13.8	5615	74.9	88.6	1.93	-4.8
KIG 0768	16 42 19.9	+20 01 55	15.3	6835	16.0	171.7	1.58	-2.8
KIG 0769	16 42 42.3	+22 36 41	13.2	4272	57.0	180.7	3.00	-1.2
KIG 0798	17 17 12.1	+73 29 21	13.2	1254	16.7	62.7	0.30	-0.5
KIG 0824	17 39 02.8	+41 19 32	14.8	5352	71.3	254.2	4.15	-3.2
KIG 0826	17 41 58.7	+34 36 05	15.6	^a	...	116.6	...	-2.8
KIG 0829	17 44 19.9	+61 55 45	15.2	11514	153.5	108.5	4.85	-2.8
KIG 0836	17 49 03.3	+39 57 43	15.8	^a	...	92.8	...	-2.8
KIG 0841	17 57 49.8	+45 53 21	14.01	5763	76.8	55.10	1.25	-2.9
KIG 0894	20 54 30.0	+06 37 00	14.9	^a	...	...	...	-2.8
KIG 1015	23 18 49.8	+25 06 33	14.5	4432	59.1	31.4	0.54	-2.8
KIG 1042	23 46 40.3	+30 42 13	14.6	5248	70.0	57.0	1.20	-2.8
KIG 1045	23 52 45.5	+05 38 11	12.6	3848	50.3	88.1	1.30	-4.8

^aunknown redshift or inappropriate for distance determination

^bDistance from us to the galaxy assuming $H_0=75 \text{ km s}^{-1} \text{ Mpc}^{-1}$

^cprojected distance from the galaxy to its first nearest neighbor

^dmorphological type as given in LEDA

TABLE 2.2
ISOLATED EARLY-TYPE GALAXIES FROM THE FASANO & BONOLI SAMPLE

Galaxy	R.A. (1950)	DEC (1950)	B_T [mag]	VEL [km/s]	Dist. Mpc ^b	$\theta(NN)$ ['] ^c	Dist(NN) Mpc	Type ^d
UGC 1503	01 58 24.6	+33 05 14	14.4	6999	67.8	30.8	0.61	−4.8
UGC 5705	10 28 19.1	+29 03 13	13.8	1446	19.3	29.3	0.16	−4.7
UGC 6159	11 04 00.9	+20 21 22	14.0	1222	16.3	18.8	0.10	−4.8
UGC 6504	11 28 29.4	+23 02 37	14.1	6490	86.5	43.8	1.10	−4.8
UGC 6810	11 48 06.8	+20 17 35	14.4	6166	82.2	23.2	0.55	−4.9
UGC 7115	12 05 33.0	+25 30 58	14.4	6788	90.5	10.0	0.26	−4.9
UGC 7681	12 29 42.0	+10 31 30	13.8	1372	18.3	43.2	0.23	−4.8
UGC 7767	12 33 33.4	+73 57 01	13.8	1281	17.1	3.8	0.02	−4.8
UGC 9070	14 08 21.3	+48 46 55	14.3	1891	25.2	13.9	0.10	−4.8
UGC 9278	14 26 05.2	+18 08 53	14.3	5632	75.1	125.2	2.74	−4.9
UGC10352	16 19 34.9	+01 23 55	13.7	4970	66.3	162.1	3.13	−4.4

^aunknown redshift or inappropriate for distance determination

^bDistance from us to the galaxy assuming $H_0=75 \text{ km s}^{-1} \text{ Mpc}^{-1}$

^cprojected distance from the galaxy to its first nearest neighbor

^dmorphological type as given in LEDA

TABLE 2.3
EARLY-TYPE GALAXIES IN HICKSON COMPACT GROUPS^a

Galaxy	R.A. (1950)	DEC (1950)	B_T [mag]	VEL [km/s]	Dist. Mpc ^b	$\theta(NN)$ ['] ^c	Dist(NN) Mpc ^d	Type ^e
HCG 10b	01 22 50.1	+34 27 11	12.7	4862	64.0	8.30	0.15	-3.0
HCG 34a	05 19 04.5	+06 38 28	14.2	8997	119.0	0.56	0.02	-2.7
HCG 37a	09 10 39.8	+30 11 59	12.9	6745	89.9	0.66	0.02	-4.7
HCG 40a	09 36 23.0	-04 37 21	13.4	6628	88.4	0.63	0.02	-4.7
HCG 40b	09 36 24.5	-04 38 22	15.0	6842	88.4	0.63	0.02	-2.5
HCG 61a	12 09 47.0	+29 27 28	12.8	3784	50.4	2.56	0.04	-3.0
HCG 68a	13 51 19.6	+40 31 42	11.8	2162	28.8	1.22	0.01	-2.0
HCG 68b	13 51 19.7	+40 32 53	12.2	2635	35.1	1.22	0.01	-2.0
HCG 68d	13 51 39.0	+40 35 00	13.7	2408	32.1	4.19	0.04	-1.9
HCG 82a	16 26 28.5	+32 57 31	14.1	11177	149.0	1.15	0.05	-1.9
HCG 93a	23 12 46.8	+18 41 19	12.6	5140	68.5	3.00	0.06	-3.0

^aExcept from the morphological type code, all the data from Hickson (1994)

^bDistance from us to the galaxy assuming $H_0=75 \text{ km s}^{-1} \text{ Mpc}^{-1}$

^cprojected angular distance from the galaxy to its first nearest neighbor

^dprojected distance from the galaxy to its first nearest neighbor

^ethe morphological type code was taken from LEDA

TABLE 2.4
SAMPLE OF EARLY-TYPE GALAXIES WITH DETECTED ISM

Galaxy	R.A. (1950)	DEC (1950)	B_T [mag]	VEL [km/s]	Dist. Mpc ^b	$\theta(NN)$ ['] ^c	Dist(NN) Mpc ^d	Type ^e
N0759	01 54 52.8	+36 05 57	13.8	4803	64.0	5.8	0.11	-4.8
N0807	02 02 03.2	+28 44 57	13.6	4748	63.3	12.0	0.21	-4.8
N0855	02 11 10.7	+27 38 39	13.3	575	7.7	178.3	0.40 ^a	-4.8
U1503	01 58 24.2	+33 05 19	14.4	5085	67.8	30.8	0.61	-4.8
N2128	06 00 15.6	+57 37 51	13.8	3142	41.9	88.9	1.08	-3.0
N2320	07 01 49.5	+50 39 24	12.9	5725	76.3	10.9	0.26	-4.8
N2534	08 08 56.8	+55 49 26	13.7	3676	49.0	42.2	0.60	-4.9
N2672	08 46 31.3	+19 15 40	12.6	4103	54.7	0.58	0.01	-4.7
N2768	09 07 45.2	+60 14 40	10.8	1408	18.8	40.1	0.21	-4.4
N2810	09 17 18.8	+72 03 28	13.2	3562	47.5	18.2	0.25	-4.8
N3597	11 12 14.0	-23 27 24	13.7	3484	46.4	66.0	0.89	-0.3
N3656	11 20 50.5	+54 07 08	13.4	2871	38.3	1.2	0.01	0.0
N3928	11 49 10.1	+48 57 34	13.2	981	13.1	26.0	0.10 ^a	-4.7
N5217	13 31 40.7	+18 06 53	13.8	1087	14.5	48.4	1.52	-4.9
N5666	14 30 43.3	+10 43 47	13.4	2221	29.6	37.7	0.32	7.0
N6524	17 57 50.0	+45 53 21	14.0	5579	74.4	55.1	1.19	-2.9
N6702	18 45 30.9	+45 39 03	13.2	4724	63.0	119.0	2.18	-4.8
N7052	21 16 20.9	+26 14 15	13.8	4764	63.5	39.4	0.81	-4.8

^aunknown redshift or inappropriate for distance determination

^bDistance from us to the galaxy assuming $H_0=75 \text{ km s}^{-1} \text{ Mpc}^{-1}$

^cprojected angular separation from the galaxy to its first nearest neighbor

^dprojected distance from the galaxy to its first nearest neighbor

^ethe morphological type code was taken from LEDA

Figure 2.1 Points in the top panel give the cumulative LF for galaxies with known B_T and redshift in the KIG. The curves were obtained assuming a Schechter LF with $\alpha = -1.5$ (continuous) and $\alpha = -1.25$ (dashed). The histograms in the lower panel give (from top to bottom) the redshift distribution in: the KIG, ETs in the KIG, and our KIG sub-sample. The dot-dashed line is the expected distribution for a homogeneous distribution with the same apparent magnitude distribution.

CHAPTER 3

CCD SURFACE PHOTOMETRY

3.1. Introduction

Since the early 1980's, the advent of CCDs has resulted in significant developments in astronomical research. The linearity, large dynamic range, and high quantum efficiency of CCDs has permitted one to obtain digital images of superior quality. The study of the surface photometry of early-type galaxies, in particular, has benefited greatly from the use of these electronic devices. There is an extensive list of investigations that have done these kind of studies. Some often-cited references include: Lauer (1985), Carter (1987), Jedrzejewski (1987), Bender et al. (1988), Bender et al. (1989), Franx et al. (1989), Peletier et al. (1990), Capaccioli et al. (1990), Goudfrooij et al. (1995). These workers have shown the usefulness of the surface photometry techniques as a means to study early-type galaxies. They have found that the isophotes of ellipticals are not perfect ellipses, but present small but significant deviations, that can deviate by as much as 1% from the perfect elliptical isophote shape. One of the most relevant aspects of surface photometry studies, is that these deviations are correlated with several properties of the galaxies. Properties such as the degree of "boxiness" or "diskiness", the presence of dust,

and whether ellipticals are radio luminous or bright at x-ray wavelengths are a few of the properties that have been found to be correlated with the deviations of the isophotes. In this work, the surface photometry technique is used to examine the galaxies in the four samples.

3.2. Observations

The observations for the optical data were obtained at the Steward Observatory 90" telescope at Kitt Peak, Arizona. These observations were carried out in several observing runs over a period of approximately two years (from the fall of 1995 to the summer of 1997). For each object, broad-band images at the B and I bands were taken. These bands were chosen to obtain wide baselines to study the color properties of the galaxies, without heavily compromising the signal to noise ratio of the images. In order to take full advantage of the characteristics of the two CCD detectors available at the 90 inch during the period of these observations, a different CCD was used for each of the filters. This forced us to work with just one filter per observing night.

The B band observations were carried out with a 1200x800 pixels, thinned, backside illuminated CCD, with quantum efficiency very close to one. Although the quantum efficiency of this CCD remains very high even at the I band, the image quality at those wavelengths was severely affected by fringing. For that reason, this CCD was not used for the I band. Instead, the I band observations were made with a 2048x2048 pixels, front illuminated CCD which was optimized for observations in the red, and does not present significant problems with fringing. Even though this CCD does not have the high quantum efficiency of the smaller device, this disadvantage is somewhat compensated by the larger field of view,

which covers more than four times the area of the 1200x800 CCD. The large format is very convenient to carry out observations of the larger galaxies, of the compact groups of galaxies, and to obtain a wider sky coverage for a better sky-subtraction for all the galaxies. Both CCDs have a pixel scale of $0.15'' \text{ pix}^{-1}$, and were binned by a factor of 2 in both rows and columns. This allowed us to reduce the read out time by a factor of 4 without sacrificing the quality of the data, since the seeing was rarely below $1''$. The average seeing for all our observations (full width at half maximum of stars in the field of the galaxies) was $1''.66$ for the B band, and $1''.45$ for the I band). For the B band, we used a 2 inch $\times$ 2 inch nearly Mould filter. For the I band, we used a 4 inch $\times$ 4 inch WFPC2 F814W filter. Since we needed deep images of relatively faint galaxies, we used the auto-guider for all the galaxy observations in the B and I bands. The exposure times were chosen so that the centers of the galaxies were clearly in the linear regime of the CCD (the exposure times varied from 2 to 10 minutes). Normally 3 or 4 frames of each galaxy were taken (for each filter). Between exposures, the telescope was pointed to a slightly different position. This procedure was followed in order to be able to remove cosmic ray hits and other blemishes on the CCD after combining the images. In general, the B band data were taken on darker nights than the I band data, which was taken during gray or even bright time (i.e. with the full moon). The log of observations for the galaxies in the Karachentseva sample is presented in Table 3.1, whereas the log for the galaxies in the other three samples is presented in Table 3.2.

Several standard stars were recorded during each observing night. Most of these were selected from Landolt (1992). In most cases, red stars were chosen for being more similar in color to the galaxies investigated. Unfortunately, most observations (particularly those in the B band) were carried out under non-photometric sky conditions. For this reason, this work will not claim to have

absolute photometry.

3.3. Data Reductions

The data reductions were carried out applying standard reduction techniques using tasks from the IRAF package, as described by Massey (1992). In the following description, the IRAF jargon will be used. More information about IRAF can be found in Barnes (1992) and in Massey (1992). We used the task *zerocombine* to combine the zero second integration exposures (bias frames), and *flatcombine* to combine the dome flat fields. The task *ccdproc* was used to subtract the pedestal level, to trim the images, to subtract the zero second exposures, and to divide by the normalized flat field frame. In cases when the flat fielded objects resulted with large gradients, we made use of twilight flats with the purpose of correcting the images to within 1% level throughout the field of the CCD. However, in some instances, the 1% goal was not achieved due to light contamination produced by scattered light from bright objects close to the field under investigation. For critical cases with very large gradients the sky was fitted with low order polynomials, using the *illumination* task in the *longslit* package. Cosmic rays were found and replaced by the average of the nearest neighbor pixels using the *cosmicrays* task.

For each filter the reduced images of each galaxy were combined using the position of stars common to all the frames as reference. This was done as follows. The centers of the stars in each frame were found using centering algorithms such as *daofind* in the *daophot* photometry package or *imeam* in the *images* package. The task *lintran* was used to calculate the offsets needed to bring the objects to a common center. The images were combined with *combine* using the *avsigclip* option to remove cosmic rays or bad pixels in the CCD. In the few cases where no

common stars were found in the galaxy frames. the center of the galaxy was used as a reference. Provided the center of the galaxy had a sharp peak, this procedure was found to be quite reliable. Overall, shifting the images produced errors which were a small fraction of the pixel size. Galaxies observed on different nights (with the same filter) were combined using three or more stars to get good alignments, since in those cases, the scale as well as the orientation of the CCD could be different. In such situations, a simple shift did not produce the desired alignment, and more general coordinate transformations of the images were required. Such transformations were accomplished using the tasks *geotran* and *geomap* in the *images* package. The last step was to orient the images to the familiar “North is up, East to the left” configuration.

3.4. Standard Stars and Photometric Quality of the Observations

After the standard star frames had been reduced according to the procedure described above, the photometric calibrations were done using tasks from the *Daophot* package available in IRAF. First, the task *daofind* was used to locate the centroids of the standard stars within each frame. Then the task *photcal* was used to do aperture photometry on the stars, to obtain the instrumental magnitudes. To transform the instrumental magnitudes to real magnitudes (Landolt 1992), transformation equations with coefficients appropriate to the site of the 90” telescope at Kitt Peak (KPNO CCD Direct Imaging Manual, Massey et al. 1997) were used. In this way the magnitude zero points were determined. Since most observations were taken under non-photometric conditions, the magnitude zero points were quite different for different nights. Furthermore, the magnitude zero points also presented variations throughout the same night. As a minimum (but not sufficient) requirement for a photometric night one would expect, that the

magnitudes of stars in the field of the galaxies should be constant. But in many cases this was not the case. In the few cases of photometric nights we found that the variation on the magnitude of the stars was of the order of $\sim .01$ mag.

3.4.1. Photometric Calibrations

For the photometric nights, the photometric calibrations were done using standard stars taken during the nights of the observations. The zero points found were then used to calibrate the galaxies. For the non-photometric nights, the same zero points found during the photometric nights were used. No absolute photometry is claimed in this work. Calibrating with aperture photometry published by other authors (Burstein et al. 1987, for instance) was not a choice, since for many of the galaxies in this work no previous surface or aperture photometry was available in the literature. The only real alternative is to take short exposures of these galaxies during photometric nights. This is something that needs to be done in the near future. However, the most valuable contributions of this thesis do not depend on the results of absolute photometry. Therefore, we shall concentrate on the structural information that is obtained from the surface photometry analysis.

After calibrating the galaxies to one airmass, they were corrected for Galactic extinction and K-corrections were applied. Galactic extinction values from Burstein & Heiles (1984) were used for the extinction correction. K-corrections for the B-band were taken from Pence (1976). For the I band, the K corrections were calculated using the expression $2.5\log(1+z)$ in Goudfrooij (1995).

3.5. Surface Photometry Analysis

For the surface photometry, the *ellipse* task in the STSDAS package (Jedrzejewski 1987) was used. This permitted to obtain profiles of the relevant variables as a function of an effective radius (or the semi-major axis). The *mark* and *region* parameters in the *ellipse* task were used extensively. The use of these parameters permit to block bright stars or any other defects in the image that can distort the isophotes.

The following information is obtained through the surface photometry analysis: the mean intensity, which is later translated into the surface brightness magnitude; the position angle; the ellipticity; and the harmonic amplitudes terms. The most important are the third (S_3 and C_3) and fourth (S_4 and C_4) order Fourier coefficients in the expansion:

$$I = I_0 + \Sigma(S_n \sin(n\theta) + C_n \cos(n\theta)).$$

The harmonic amplitudes are indicators of the departure of the light distribution from perfect ellipses, and are important because they are related to properties of early-type galaxies (see for instance, Bender 1989 or Goudfrooij 1994). The most straightforward coefficient for interpretation is the C_4 coefficient. From symmetry arguments, it is easy to see that if the sign of this coefficient is positive, the galaxy must have a disk component, whereas if it is negative, the galaxy is boxy. The presence of dust can be inferred from the third order Fourier coefficients, and very often its presence affects most of the profiles.

There are several sources of errors that can influence the results from surface photometry. Some of these have already been discussed: sky subtraction error, seeing, non-flatness in the detector. According to Busko (1996), the local radial

gradient error σ_I/I , suffices to describe the precision to which a given isophote can be fitted. The *ellipse* task calculates the errors in the intensity and local gradient from the RMS scatter of intensity along the fitted ellipse. It is shown by Busko (1996), that the intensity errors are slightly underestimated by the *ellipse* task, which causes an underestimation trend that depends on the particular magnitude chosen. In order to have more realistic (larger) error bars, we have added in quadrature the error in intensity obtained by the *ellipse* task with an upper limit for the sky subtraction error. After studying regions of the CCD that are sufficiently far from the galaxies studied, we have found that a value of 2% of the sky value is an appropriately high upper limit for the sky-subtraction error. The errors in the ellipse geometry parameters (errors in ellipticity and position angle) are obtained from the internal errors in the harmonic fit, after removing the first 2 harmonics. The harmonic amplitude errors (errors in $S3$, $C3$, $S4$, and $C4$) are obtained from the fit error after removing all the harmonics up to, and including the one being considered (Busko 1996). The errors in the geometry parameters are unbiased and accurate for σ_I/I smaller than ~ 0.5 . For $\sigma_I/I > 0.5$ these errors are increasingly underestimated. The harmonic amplitude errors show more complex behavior. For instance for $\sigma_I/I \sim 0.1$ there is a small underestimation bias, whereas, for $\sigma_I/I > 0.3$ the errors are usually overestimated. Another general result from Busko (1996), is that round isophotes $\epsilon < 0.1$ cannot be fitted with the same precision as more elliptical isophotes, for a given S/N.

The results of the optical surface photometry are presented in figures 3.1.1 - 3.1.47. In these figures, the semi-major axis (referred to as radius in the figures) of the elliptical isophote is plotted on the horizontal axis in a logarithmic scale. For the surface brightness magnitude, the data is presented over a range from 1 to approximately 100 arc seconds in radius, depending on the size of the galaxy. For

the rest of the profiles: ellipticity, position angle, and third and fourth order Fourier coefficients, the range is cut by a lower and an upper effective threshold radius. The lower threshold is due to the effect of seeing and to non-circular contributions to the point spread function, which can be produced by wind, systematic errors in the guiding, and probably other causes (there was a problem with coma in one of our runs with the B filter). The lower threshold has been set to 3 arc seconds which is approximately twice the seeing value. This appears to be a reasonable value for most galaxies. For some of the galaxies, however, the problems mentioned above extend well beyond 3 arc seconds, in some cases reaching up to 10 arc seconds. This problem appears to be more acute for the *B* data. The upper threshold is due to the lower signal to noise ratio at the outer regions of the galaxies, and this clearly depends on the diameter and light distribution of the galaxies.

Surface photometry is presented for galaxies that appear to be early-type galaxies. Several galaxies in the KIG and in the ISM selected sample, however, do not fulfill this requirement due to the complex structures they possess (spiral arms, merger signatures, dust lanes, etc.). For such galaxies the *ellipse* task simply does not work, or does not produce reliable results.

3.6. Comparison of the results

Due to the non-photometric nature of a significant fraction of the data, attention is focused on comparing the structural information that results from the surface photometry analysis. For an internal comparison, the data for the *B* and *I* bands are plotted (with different symbols) on the same figures (3.1-3.49). The profiles are not expected to be exactly alike, because the presence of dust or color differences in the stellar populations may produce real differences in the profiles. However, for

smooth early-type galaxies, the profiles are expected to be reasonably similar at B and I bands. In fact this turns out to be the case. The most ‘clean’ early-types shown in the Appendix A (which contains the images of the galaxies), are the ones that are the most similar in the B and I . For some of the galaxies, the discrepancies occur at small radii in the ellipticity or in some of the other parameters. As it was discussed above, this effect occurs when the PSF is non circular. Examples of this can be seen in the ellipticity profiles of KIG 83, UGC 6159, and NGC 4692 (Figs. 3.1, 3.17 and 3.44). But unlike the previous effect which is produced by poor point spread functions, there are real differences among the data at different bands which are due to dust. We have had the opportunity to study this effect, thanks to the inclusion of dusty early-types in the sample of galaxies with detected ISM. Profiles that otherwise would look similar, appear quite different whenever dust is present. A good illustration of this can be seen in the profiles of NGC 2768 (Fig. 3.42). Aside from deviations due to effects like the ones described above, the profiles resemble one another, which provide an internal confirmation that the shapes of the profiles described in this thesis are correct.

For external comparisons, the results of this work are compared with those of other investigators that present surface photometry for the same objects. The sources that have more objects in common with our data are those of Djorgovski (1985), and Fasano and Bonoli (1989). Djorgovski includes several of the brightest galaxies studied in this thesis. In the case of Fasano and Bonoli, the coincidence is not accidental. One of the reasons these galaxies were chosen is because surface photometry is available to compare the results (even though in their case they have r -band data rather than B and I). The data of the authors mentioned above has been incorporated in Figs. 3.1-3.49 using special symbols to prevent confusion with the data of this work. Aside from the previous two sources there are works in which

there is overlap with one or two galaxies. Such is the case of Goudfrooij (1994) and Peletier (1990). Overall, the gross agreement is quite good, but the greater detail that can be seen in this work is quite evident. This is partly due to the great improvements of CCDs over the years, as well as to the high image quality of the 90 inch telescope.

3.7. Color Gradients

It has been known for some time (Sandage & Visvanathan 1978) that giant elliptical galaxies present small color gradients. These gradients are such, that the colors in ellipticals are redder towards the center of the galaxy. The average color gradient of the sample of ellipticals with $B_T < 12$ mag studied by Goudfrooij is $0.063 \pm .005$ mag per decade in radius in B-V, which is consistent with the value previously found by Bender & Mollenhoff (1987). Most investigators agree that the color gradients are due to metallicity gradients, and that these are produced in the process of formation and evolution of elliptical galaxies. However, some investigators have suggested in recent years that dust and age can also play a role in explaining the color gradients.

To obtain color index profiles for the galaxies for which data with the two filters is available, the surface brightness magnitude of I was subtracted from B for each value of the semi-major axis. The results for the color index profiles are presented in the graphical form in the upper right panels of figures 3.1.1 - 3.1.47, when both B and I data are available. They are presented in tabular form (along with other properties of the galaxies) in Chapter 5, Table 5.2. For most of the smooth ellipticals, the same trends in the gradients are observed as those that have been found by other workers. There is only one galaxy with $B - I$ information, for

which a direct comparison with this data can be made. Goudfrooij (1994) presents the $B - I$ color index for NGC 821, which is the same as KIG 89. The agreement on the color index is good. Goudfrooij found a color gradient of -0.07 whereas this study finds $-0.08 \text{ mag arcsec}^{-2}$ per decade in radius. The mean B-I color, however, differs by 0.2 magnitudes. This is probably due to the non-photometric nature of our data, but the shapes of the profile are similar.

Besides the smooth color gradients, many of the galaxies studied exhibit large local variations in the profile of $B - I$. This kind of profile is observed in most of the ellipticals known to contain dust lanes. A similar effect is seen among the galaxies that exhibit spiral or perturbed structures. Thus, in some cases, this structure in the profiles might indicate that the galaxy is not an elliptical galaxy.

3.7.1. The color magnitude diagram for the 4 samples

In view of the great difference in properties of galaxies with different luminosities, it is important to know the distributions of absolute magnitudes and colors for the galaxies in the 4 different samples. The top panel of Figure 3.49 gives the color magnitude diagram for all the objects for which B and I surface photometry data have been obtained in this work. The vertical axis of this figure gives the blue absolute magnitude M_B , corrected for extinction. The values for the absolute magnitudes M_B , were taken from the LEDA database, and the extinction corrections were extracted from the NED. Most of these corrections are from Burstein (1987), or from the most recent work of Schlegel et al. (1998). For comparison, the bottom panel of Figure 3.49 gives the color magnitude diagram for the sample of elliptical galaxies with $B_T \leq 12$ from Goudfrooij (1994). Both M_B as well as $(B - I)$ were taken from Goudfrooij (1994). Taking $M_B < -19$ as a definition for giant ellipticals, it can be seen that most of the galaxies in the

samples (except for the Fasano and Bonoli) fit in the category of giants.

3.8. Residual Images

Dust, galaxy disks, spiral structure, globular clusters, merger signatures, star forming regions, as well as other features can in principle be seen in galaxy images. But, as pointed out by Ebneter et al. (1988), one of the main problems in searching for such morphological features in elliptical-like galaxies is suppressing the strong radial intensity gradient of the galaxy. The solution to this problem is to make a smooth elliptical model for the galaxy. In this work, the results from *ellipse* (described above) are used as input in the *bmodel* task to make an elliptical model for the galaxy. The original image is then divided or subtracted by the model to eliminate the underlying smooth light distribution of the galaxy. The residual image that results, highlights the galaxy features. As in Ebneter et al. (1988), best results were found by dividing (rather than subtracting) the galaxy image by the elliptical model. The maximum values of the residual image are typically of the order of a few percent, and in most cases smaller than 5.0% for ellipticals without obvious dust lanes or spiral features. If dust lanes are present, the maximum can be as large as 10.0%. On the other hand, if the galaxies have clear spiral features, this percentage can be larger than 20.0%. It is important to point out, however, that it is not unusual to see features in the residuals that are not real. Such spurious features are usually due to not having centered correctly the model image or to bad seeing and guiding errors. Other artifacts are produced by bright stars. In such cases, bright elliptical shells are often seen. We have essentially eliminated the second problem, by masking the bright stars. Another source of spurious effects is due to bad flat fields. Finally, trying to force the surface photometry on a galaxy with strong spiral arms often leads to questionable residual images (as well as

questionable surface photometry). For this reason we do not show residuals for the objects of that kind.

Appendix A presents images for the galaxies and residual (quotient) images for the objects for which surface photometry was performed. In spite of the cautionary words given above, except perhaps for a few galaxies that present small features near the center, and for features indicated in the comments for individual objects the features seen in our residual images appear to be real. The large X structures are due to disks, whenever they coincide with the semi-major and semi-minor axes. Boxey galaxies have X structures that have a rotation of 45° with respect to those axis. Spiral arms, dust lanes, merger signatures, stars and globular clusters can be easily seen in the residual images.

TABLE 3.1.1
JOURNAL OF OBSERVATIONS

Galaxy	Date _B (UT)	T _B (sec)	FWHM _B (arc sec)	Date _I (UT)	T _I (sec)	FWHM _I (arc sec)
KIG 0074	...	...	...	Sep 1995	300	1.10
KIG 0083	Feb 1997	2400	1.29	Oct 1997	2400	1.29
KIG 0089	Nov 1996	600	1.29	Oct 1997	720	1.29
KIG 0120	Nov 1996	1800	1.53	...	...	...
KIG 0128	Nov 1996	1500	1.65	Oct 1997	2400	1.15
KIG 0179	...	...	...	Apr 1997	1800	1.30
KIG 0248	Apr 1995	2400	2.20	...	...	...
KIG 0303	May 1996	900	1.65	Mar 1996	1440	1.38
KIG 0308	May 1996	900	1.50	...	...	...
KIG 0358	Mar 1996	2400	1.45	Mar 1996	1080	1.41
KIG 0393	Mar 1996	900	...	Mar 1996	3000	1.38
KIG 0396	Mar 1996	1500	1.60	Mar 1996	3000	1.00
KIG 0437	...	...	...	Mar 1997	720	1.41
KIG 0443	...	...	...	Mar 1997	600	1.80
KIG 0467	...	...	...	Apr 1997	1200	1.50
KIG 0501	...	...	...	Mar 1997	1500	1.50
KIG 0503	Mar 1996	1200	1.74	Mar 1996	1800	1.00
KIG 0505	...	...	...	Mar 1997	1800	1.60
KIG 0511	...	...	...	Mar 1997	1200	1.75
KIG 0537	Apr 1997	900	1.45	...	...	...
KIG 0555	Apr 1995	600	1.45	...	...	...
KIG 0633	Apr 1997	300	1.70	Mar 1997	1200	1.57
KIG 0697	...	...	...	Apr 1997	1200	1.95
KIG 0705	July 1997	1200	1.45	Mar 1997	2400	1.76
KIG 0714	July 1997	1200	1.54	July 1997	1200	1.74
KIG 0721	...	...	...	Mar 1997	1200	1.80
KIG 0732	May 1996	2100	1.44	Mar 1997	1800	1.50
KIG 0768	May 1997	3000	1.38	May 1996	780	1.23
KIG 0769	May 1996	600	1.35	May 1996	180	1.20
KIG 0798	May 1996	300	1.60	Mar 1997	2400	1.90
KIG 0824	May 1996	1800	1.41	Sep 1995	1500	1.14
KIG 0829	May 1996	900	1.35	...	...	...
KIG 0836	May 1995	2400	1.37	...	...	...
KIG 0841	May 1996	600	1.10	Oct 1996	1800	1.71
KIG 0894	July 1997	2400	1.35	Oct 1996	1860	1.55
KIG 1015	Nov 1996	3000	1.56	Oct 1996	1500	1.44
KIG 1042	Nov 1996	3900	1.80	Sep 1995	1500	1.25
KIG 1045	Nov 1996	3600	1.50	Oct 1996	1020	1.35

TABLE 3.1.2
JOURNAL OF OBSERVATIONS

Galaxy	Date _B (UT)	T _B (sec)	FWHM _B (arc sec)	Date _I (UT)	T _I (sec)	FWHM _I (arc sec)
UGC 5705	May 1996	1500	1.90	Feb 1996	960	1.25
UGC 6159	May 1996	1200	2.50	Mar 1996	1080	1.38
UGC 6504	May 1996	1800	1.65	Mar 1996	1080	1.38
UGC 6810	May 1996	2100	2.30	Feb 1996	780	1.17
UGC 7115	May 1996	1800	1.66	...	...	...
UGC 7681	May 1996	1800	1.78	...	...	...
UGC 7767	May 1996	1800	1.51	Feb 1996	720	1.23
UGC 9070	May 1996	1500	1.50	May 1996	600	1.80
UGC 9278	May 1996	1500	1.53	May 1996	900	1.35
UGC 10352	May 1996	2100	1.53	May 1996	780	1.30
UGC 10599	May 1997	2400	1.57	May 1997	720	1.43
HCG 10b	July 1997	1200	1.40	Oct 1996	1500	1.38
HCG 34a	Feb 1996	2400	1.50	...	...	...
HCG 37a	Feb 1996	1800	1.80	Feb 1996	900	1.16
HCG 40a,b	Feb 1997	1800	2.01	Mar 1997	1200	1.74
HCG 61a	May 1997	1500	2.34	...	...	...
HCG 68a,b	Feb 1997	1800	2.30	Jun 1996	1200	1.25
HCG 68d	Feb 1996	2100	1.73	Feb 1996	1560	1.08
HCG 82a	July 1997	1800	1.41	...	...	...
HCG 93a	July 1997	1800	1.42	Oct 1996	960	1.80
NGC 0759	July 1997	1200	1.47	...	...	...
NGC 0807	Feb 1997	1800	1.98	Oct 1996	1300	1.40
NGC 0855	Feb 1997	1800	1.90	...	...	...
NGC 2128	Feb 1996	1200	1.30	...	...	...
NGC 2320	Nov 1996	1200	1.31	Feb 1996	1440	1.19
NGC 2534	Feb 1997	1800	2.09	Feb 1996	720	1.44
NGC 2672	Feb 1997	1200	1.80	...	...	...
NGC 2768	Feb 1997	1200	2.10	Feb 1996	420	1.10
NGC 2810	May 1996	900	1.50	Feb 1996	1440	1.35
NGC 3656	Feb 1997	1800	1.90	Apr 1997	1200	1.35
NGC 3928	Feb 1997	1200	2.50	Mar 1996	760	1.34
NGC 5217	Feb 1997	600	1.89	May 1996	1200	1.09
NGC 5666	May 1996	1200	1.30	Feb 1996	1080	1.30
NGC 6166	July 1997	1200	1.58	May 1997	600	...
NGC 6702	May 1996	2100	1.32	Mar 1997	1650	1.56
NGC 7052	May 1996	1500	1.56	May 1996	2700	...

KIG 83

Figure 3.1 Radial profiles of galaxy KIG 83. Plotted are the B and I surface brightness, $B - I$ color index, ellipticity, position angle, and the coefficients of $\sin(3\theta) \cos(3\theta)$, $\sin(4\theta)$ and $\cos(4\theta)$ (where θ is the position angle of the ellipse, and the coefficients are referred as S3, C3, S4, and C4 in the figure). Except for the surface brightness, the profiles have been cutoff at small and large radius (see the text). All profiles, are plotted as a function of the semi-major axis of the ellipse. The pentagons are from Fasano and Bonoli (1989), and are shown for comparison.

KIG 89

Figure 3.2 Same as in Fig 3.1, but for galaxy KIG 89.

KIG 120

Figure 3.3 Same as in Fig 3.1, but for galaxy KIG 120.

KIG 303

Figure 3.4 Same as in Fig 3.1, but for galaxy KIG 303.

KIG 358

Figure 3.5 Same as in Fig 3.1, but for galaxy KIG 358.

KIG 393

Figure 3.6 Same as in Fig 3.1, but for galaxy KIG 393.

KIG 396

Figure 3.7 Same as in Fig 3.1, but for galaxy KIG 396.

KIG 503

Figure 3.8 Same as in Fig 3.1, but for galaxy KIG 503.

KIG 732

Figure 3.9 Same as in Fig 3.1, but for galaxy KIG 732.

KIG 768

Figure 3.10 Same as in Fig 3.1, but for galaxy KIG 768.

KIG 824

Figure 3.11 Same as in Fig 3.1, but for galaxy KIG 824.

KIG 841

Figure 3.12 Same as in Fig 3.1, but for galaxy KIG 841.

KIG 1015

Figure 3.13 Same as in Fig 3.1, but for galaxy KIG 1015.

KIG 1042

Figure 3.14 Same as in Fig 3.1, but for galaxy KIG 1042.

KIG 1045

Figure 3.15 Same as in Fig 3.1, but for galaxy KIG 1045.

UGC 5705

Figure 3.16 Same as in Fig 3.1, but for galaxy UGC 5705. The pentagons shown for comparison are from Fasano and Bonoli (1989).

UGC 6159

Figure 3.17 Same as in Fig 3.1, but for galaxy UGC 6159. The pentagons shown for comparison are from Fasano and Bonoli (1989).

UGC 6504

Figure 3.18 Same as in Fig 3.1, but for galaxy UGC 6504. The pentagons shown for comparison are from Fasano and Bonoli (1989).

UGC 6810

Figure 3.19 Same as in Fig 3.1, but for galaxy UGC 6810. The pentagons shown for comparison are from Fasano and Bonoli (1989).

UGC 7115

Figure 3.20 Same as in Fig 3.1, but for galaxy UGC 7115. The pentagons shown for comparison are from Fasano and Bonoli (1989).

UGC 7681

Figure 3.21 Same as in Fig 3.1, but for galaxy UGC 7681.

UGC 7767

Figure 3.22 Same as in Fig 3.1, but for galaxy UGC 7767. The pentagons shown for comparison are from Fasano and Bonoli (1989).

UGC 9070

Figure 3.23 Same as in Fig 3.1, but for galaxy UGC 9070. The pentagons shown for comparison are from Fasano and Bonoli (1989).

UGC 9278

Figure 3.24 Same as in Fig 3.1, but for galaxy UGC 9278. The pentagons shown for comparison are from Fasano and Bonoli (1989).

UGC 10352

Figure 3.25 Same as in Fig 3.1, but for galaxy UGC 10352. The pentagons shown for comparison are from Fasano and Bonoli (1989).

UGC 10599

Figure 3.26 Same as in Fig 3.1, but for galaxy UGC 10599.

HCG 10b

Figure 3.27 Same as in Fig 3.1, but for galaxy HCG 10b.

HCG 34a

Figure 3.28 Same as in Fig 3.1, but for galaxy HCG 34a.

HCG 37a

Figure 3.29 Same as in Fig 3.1, but for galaxy HCG 37a.

HCG 40a

Figure 3.30 Same as in Fig 3.1, but for galaxy HCG 40a.

HCG 40b

Figure 3.31 Same as in Fig 3.1, but for galaxy HCG 40b.

HCG 61a

Figure 3.32 Same as in Fig 3.1, but for galaxy HCG 61a.

HCG 68a

Figure 3.33 Same as in Fig 3.1, but for galaxy HCG 68a.

HCG 68b

Figure 3.34 Same as in Fig 3.1, but for galaxy HCG 68b.

HCG 68d

Figure 3.35 Same as in Fig 3.1, but for galaxy HCG 68d.

HCG 82a

Figure 3.36 Same as in Fig 3.1, but for galaxy HCG 82a.

HCG 93a

Figure 3.37 Same as in Fig 3.1, but for galaxy HCG 93a.

NGC 759

Figure 3.38 Same as in Fig 3.1, but for galaxy NGC 759.

NGC 807

Figure 3.39 Same as in Fig 3.1, but for galaxy NGC 807. The pentagons shown for comparison are from Djorgovski (1985).

NGC 2128

Figure 3.40 Same as in Fig 3.1, but for galaxy NGC 2128.

NGC 2320

Figure 3.41 Same as in Fig 3.1, but for galaxy NGC 2320.

NGC 2768

Figure 3.42 Same as in Fig 3.1, but for galaxy NGC 2768. The pentagons shown for comparison are from Djorgovski (1985).

NGC 2810

Figure 3.43 Same as in Fig 3.1, but for galaxy NGC 2810.

NGC 4692

Figure 3.44 Same as in Fig 3.1, but for galaxy NGC 4692. The pentagons shown for comparison are from Djorgovski (1985).

NGC 5217

Figure 3.45 Same as in Fig 3.1, but for galaxy NGC 5217.

NGC 5666

Figure 3.46 Same as in Fig 3.1, but for galaxy NGC 5666.

NGC 7052

Figure 3.47 Same as in Fig 3.1, but for galaxy NGC 7052.

NGC 7330

Figure 3.48 Same as in Fig 3.1, but for galaxy NGC 7330.

Figure 3.49 The top panel presents the color magnitude diagram for the galaxies in our samples for which we have B and I surface photometry information. The bottom panel presents the same diagram, for the sample of ellipticals with $B_T \leq 12.0$ from Goudfrooij (1994).

CHAPTER 4

K_s SURFACE PHOTOMETRY

4.1. Introduction

The development of infrared array devices, has been very beneficial to the study of galaxies. Infrared images make possible to see the stars without any significant obstruction by the dust. In fact, it was shown by Rix & Rieke (1993) in their study of M51, that even in extreme situations such as in dust lanes, the dust extinction at K does not exceed 10%. For this reason, stellar properties can be more reliably studied at infrared than at optical wavelengths (Peletier and Willner 1991, Peletier et al. 1994, Grauer & Rieke 1998). Furthermore, unlike optical observations that are strongly biased toward bright young stars, at infrared wavelengths it is possible to see the mass distributions of galaxies in a more objective way.

Since on the other hand, the shorter optical wavelengths are so affected by dust, the combination of optical and infrared photometry make possible to study dust distributions in galaxies. This kind of information is important, since the existence of dust is indispensable for star-formation as well as for nuclear activity in galaxies. By comparing the results of surface photometry at different wavelengths it is straightforward to infer whether or not dust is present in a galaxy.

4.2. Infrared Observations

The infrared observations were taken at the Steward Observatory 90-inch telescope at Kitt Peak, and at the Steward Observatory 61-inch telescope at Mt. Bigelow. These observations were taken during a period of about two years (from the fall of 1995 to the summer of 1997). The instrument used was an infrared camera with a 256×256 NICMOS3 array kindly made available by Dr. Marcia Rieke. Detailed information about the IR camera can be found in Rieke et al. (1993), and Thompson et al. (1989). The plate scale at the 90-inch telescope was approximately $0.6'' \text{pix}^{-1}$, and $0.9'' \text{pix}^{-1}$ at the 61-inch telescope, so that the field sizes were $2.5' \times 2.5'$ and $3.8' \times 3.8'$ respectively. The observations were taken using a K_s broad band filter. It was decided to observe at K_s (rather than at J or H) in order to have the widest possible wavelength baseline with respect to the optical filters used, without significantly compromising the detection level. A second reason for choosing K_s is that at this wavelength the effect of dust extinction is smaller than at J or H . The K_s filter (also known as “short K ”) covers about the same wavelength range as the regular K infrared filter, but it filters out photons at a shorter wavelength (about $0.1 \mu\text{m}$ shorter) than the K filter. The K_s filter was designed to cut out some of the bright atmospheric light in that region with the purpose of improving the S/N .

The procedure used for the observations was the following. At the beginning and sometimes also at the end of the observing night several (at least 20) dark frames were taken, with the same exposure times as those used for the different objects (typically: 0.5, 1, 20, and 30 seconds). The dark frames are necessary for reducing the data, but they can also be used as a diagnostic tool to check that the infrared array is working properly (can tell us for instance, that the dewar is warm

and needs to be refilled).

4.2.1. Observation of Galaxies

Prior to the observing run a catalog with the positions of target galaxies and SAO stars close to the line of sight of the galaxies was made. The first step during the observation, consisted of placing the nearby SAO star in a convenient place of the array. The galaxy was then found by offsetting from the star. These steps were taken to ensure that the galaxy image would be on target in a convenient place of the detector. This is particularly important, considering that the infrared observations were usually done during bright time, when the faint galaxies were difficult to see on the TV monitor. Once the position of the galaxy was secured, the next step was to find a suitable position for the sky. The telescope was moved by a little more than a field size (but never by more than three fields) in RA and/or DEC until a relatively clean field on the sky (i.e. free of bright stars or other galaxies) was found. The requirement of a clean sky field is quite important, because the sky frames are used to perform the sky subtraction, and bright objects can leave over-subtracted dark spots on the galaxy images.

For the observations of each galaxy, we took a series of 21 images, automatically beam switching the telescope back and forth between the sky and the galaxy positions. These blocks of data started and ended on a sky position, so that we could always have the information needed to determine temporal averages of the sky for each galaxy image. Each of the 21 images was actually the average of two consecutive exposures taken at the same position. The exposure times were either 20 or 30 seconds long, depending on weather conditions and on the telescope being used, to stay in the linear regime of the detector. A “double-jitter wobble” was applied to the motion of the telescope, with random components in the range

between 5'' and 10''. These random shifts made it possible to reduce or eliminate unwanted stars from the sky positions, as well as bad pixels in the array. For most galaxies three or four blocks of observations were intended, for total integration times of about 1800 seconds. However, this was not always accomplished due to bad weather. The log of galaxy observations at K_s is presented in table 4.1 for the KIG objects and in table 4.2 for the galaxies in the other three samples. The total exposure time, telescope used, and seeing are indicated in these tables.

4.2.2. Standard Star Observations

Several standard stars from the Elias infrared standards catalog (Elias et al. 1982) were observed. Whenever possible, the standards were observed at roughly the same airmass as for the galaxies. Unfortunately, photometric nights were an exception throughout this project: for this reason, no absolute photometry is claimed in this work. The procedure for the observation of the standards, was to take several exposures of the star in a mapping mode (3×3 or 4×4), with separations of about 30''. In this way, sky frames with the same exposure times as the standards were obtained. The exposure times were usually 1 second or 0.5 seconds. We avoided the brightest stars in the Elias catalog, and always checked that the data were well into the linear part of the detector. In several cases we had to defocus the telescope slightly to avoid saturation on the detector.

4.3. Data Reduction

To reduce the data, macros that work with IRAF tasks were used. Some of these macros are slight modifications of macros kindly provided by Dr. Albert Grauer. The basic reduction procedure is very similar to the one described by Grauer and Rieke (1998) and it consists of the following steps. 1) Take the average of

the dark exposures that have the same exposure time as for the objects to be reduced. 2) Subtract the average dark frame from the sky images. 3) Combine the dark-subtracted sky images with *imcombine* to obtain the flat field. 4) Obtain a time averaged sky for each galaxy position by taking the average of the contiguous (i.e. before and after) sky images. 5) The sky subtraction is accomplished by subtracting the time averaged sky frame from the galaxy frame. 6) The sky subtracted images are divided by the flat field. This produces the 60 seconds exposure reduced object frames. One of the macros mentioned above was able to perform steps 2 - 6, with considerable savings of time in the data reduction process. 7) The object frames are registered using the *imezam* task to find the centroids using common stars in the different frames. When no common stars are found on the galaxies, one can rely on the center of galaxies to register the images (this option only works if the galaxy light is centrally concentrated, which is usually the case in a typical early-type galaxy). 8) The shifts needed to bring the reference star centroids to a common point, are calculated using the IRAF task *lintran* 9) The images are median combined using the *imcombine* task from IRAF, with the option of an additive constant, to level the mean sky value for all the frames. To remove the stars in the sky frame, most of the cosmic rays, and the bad pixels on the NICMOS array, the median option is also used.

4.4. Surface Photometry of the Infrared Data

The surface photometry analysis of the infrared data is very similar to the one already described in chapter 3 for the study of the optical data. The only basic difference is due to the fact that in the infrared the sky is brighter and more variable. For this reason, the sky is subtracted during the reduction process. Therefore, the reduced infrared images do not keep information on the sky. Another

difference is that for a given total integration time, the signal to noise ratio (S/N) of the data is higher in the optical than in the infrared data. This is particularly true at large radius where the S/N ratio in the infrared becomes quite small.

4.4.1. Results of the Surface Photometry

The same procedure that was applied to obtain the surface photometry for the optical data has been used to analyze the K_s data. Briefly, it consists in running the *ellipse* task in the *stsdas* package, trying to mask any obvious stars that can distort the isophotes. The errors on the profiles are the ones obtained from the ellipse task. We refer to Chapter 3 in this thesis for more details on the surface photometry analysis. Overall, K_s surface photometry for 52 galaxies has been obtained. To our knowledge, no previous K_s data has been published for most of the galaxies in this thesis. The results are presented in graphical form in the figures 4.01 - 4.54, and will be available in digital form from the author. The plots have the same format as those presented for the optical data in the previous chapter. Whenever possible we have used the same scale as in the optical data to facilitate comparisons between the optical and the IR data.

The main result for this project is the structural information that is obtained for the galaxies. As expected, most of the dust lanes that are so evident in the optical data (especially at the B band), are not seen on the infrared plots. On the other hand $C4$ (the coefficient of $\cos(4\theta)$) is clearly seen at K_s . This confirms that the interpretation of these coefficients given by Bender et al. (1988), and others is also valid at these wavelengths. As a matter of fact, surface photometry at K_s should be ideal to study the structure of early-type galaxies due to the almost negligible extinction by dust. The only disadvantage is that up to now the S/N ratio obtained at a given ground telescope and exposure time still favors studies

at optical wavelengths. With a few notable exceptions most of the observations were done under non-photometric conditions. In some cases the sky had a few thin cirrus clouds, but there were several nights when the observations were done under cloudy skies. For these reasons, no precise absolute photometry is claimed in this work. These data will be calibrated in the near future. In the mean time, reasonable values for the K_s zero magnitudes for the 61" and the 90" observations have been adopted. In this process it has been found, that even though the data is not photometric, the spread of zero magnitudes measured from the Elias standards is not very large (less than 0.4 mag). Therefore, the K_s photometry presented in this work, while not absolute, can still be useful as a starting point for other investigations. Zero magnitude values of 18.6 for the 61" telescope data and 18.9 for the 90" data have been adopted. These values were chosen for being obtained during photometric (or near photometric nights) at these telescopes. Due to the small corrections that would be needed at K_s for these galaxies, and considering the large uncertainty (0.4 mag) in the zero magnitude, no further corrections have been applied to the data.

This chapter has presented the results of the surface photometry analysis for the K_s observations. These data will be used in connection with the results of the optical B and I data in the discussions of the next two chapters.

TABLE 4.1
JOURNAL OF OBSERVATIONS OF THE K_s DATA ^a

Galaxy	Date	TEL	EXP	FWHM
		(inch)	(sec)	(arc sec)
KIG 0083	Dec 1996	90	1200	1.30
KIG 0089	Dec 1996	90	1800	1.43
KIG 0120	Dec 1996	90	1200	1.57
KIG 0128	Dec 1996	90	1200	1.59
KIG 0248	Oct 1995	61	1800	1.37
KIG 0303	Feb 1997	61	1200	1.57
KIG 0308	Mar 1996	61	1800	1.64
KIG 0358	Jan 1997	61	960	1.20
KIG 0393	Dec 1996	90	600	1.25
KIG 0396	Feb 1997	61	1800	1.14
KIG 0437	Mar 1996	61	1800	1.81
KIG 0503	Mar 1996	61	1200	1.56
KIG 0732	May 1996	90	1600	1.20
KIG 0768	May 1997	90	2400	1.51
KIG 0769	Mar 1996	61	600	1.45
KIG 0798	May 1997	90	920	1.20
KIG 0824	Jun 1996	90	1200	1.61
KIG 0829	May 1997	90	1600	1.51
KIG 0894	May 1996	90	360	1.38
KIG 1015	Oct 1995	60	2400	1.35
KIG 1045	Dec 1996	90	1140	1.26

^aLog of observations for the KIG galaxies. The first column gives the name of the galaxy; the second specifies the month of the observing run; the third gives the total observing time; the fourth tells us which telescope was used; and the fifth the seeing value.

TABLE 4.2
JOURNAL OF OBSERVATIONS OF THE K_s DATA ^a

Galaxy	Date	TEL (inch)	EXP (sec)	FWHM (arc sec)
UGC 5705	Feb 1997	61	1800	1.14
UGC 6159	Mar 1996	61	1740	2.70
UGC 6504	Feb 1997	90	1800	1.35
UGC 6810	Mar 1996	61	480	1.51
UGC 7115	May 1996	90	1800	1.80
UGC 7767	Jun 1996	90	1800	1.48
UGC 9070	Mar 1996	61	840	1.81
UGC 9278	May 1996	90	2000	1.67
UGC 10352	May 1996	90	1600	1.62
UGC 10599	May 1997	90	1280	0.92
HCG 34a	Dec 1996	90	2220	1.20
HCG 37a	Mar 1996	61	1200	1.35
HCG 40a,b	Dec 1997	90	2100	1.75
HCG 61a	May 1997	90	1600	1.32
HCG 62a	Jun 1996	90	1800	1.45
HCG 68a,b	Mar 1996	61	600	1.17
HCG 68d	Jun 1996	90	800	1.68
HCG 79a	May 1997	90	1160	1.06
HCG 82a	May 1997	90	1480	1.14
HCG 93a	Sep 1997	90	1200	1.23
HCG 94a	Sep 1997	90	1260	1.11
NGC 0759	Dec 1996	90	1800	1.20
NGC 0807	Dec 1996	90	2400	1.46
NGC 2128	Dec 1996	90	1800	1.24
NGC 2320	Dec 1996	90	1800	1.57
NGC 2534	Feb 1997	61	1800	1.35
NGC 2672	Feb 1997	61	1740	1.41
NGC 2768	May 1996	90	1200	1.52
NGC 2810	Feb 1997	61	2160	1.25
NGC 3656	Feb 1997	90	1200	1.35
NGC 3928	Feb 1997	90	1200	1.25
NGC 4692	Jun 1996	90	1140	1.68
NGC 5217	May 1997	90	400	1.30
NGC 5666	Feb 1997	61	1200	1.17
NGC 6166	May 1997	90	960	1.32
NGC 6524	May 1996	90	1520	1.80
NGC 6702	Sep 1997	90	760	1.23
NGC 7330	Sep 1997	90	920	1.10

^aLog of observations for the non-KIG galaxies. Column two specifies the month of the observing run; column three gives the total observing time; the fourth tells us which telescope was used; and column five gives the seeing value.

KIG 83

Figure 4.1 K_S Radial profiles of galaxy KIG 83. Plotted are the surface brightness, ellipticity, position angle, and S3, C3, S4, and C4 harmonic coefficients. Except for the surface brightness, the profiles have been cutoff at small and large radius (see the text). All profiles, are plotted as a function of the semi-major axis of the ellipse.

KIG 89

Figure 4.2 Same as in Fig 4.1, but for galaxy KIG 89.

KIG 120

Figure 4.3 Same as in Fig 4.1, but for galaxy KIG 120.

KIG 248

Figure 4.4 Same as in Fig 4.1, but for galaxy KIG 248.

KIG 303

Figure 4.5 Same as in Fig 4.1, but for galaxy KIG 303.

KIG 308

Figure 4.6 Same as in Fig 4.1, but for galaxy KIG 308.

KIG 358

Figure 4.7 Same as in Fig 4.1, but for galaxy KIG 358.

KIG 393

Figure 4.8 Same as in Fig 4.1, but for galaxy KIG 393.

KIG 396

Figure 4.9 Same as in Fig 4.1, but for galaxy KIG 396.

KIG 437

Figure 4.10 Same as in Fig 4.1, but for galaxy KIG 437.

KIG 503

Figure 4.11 Same as in Fig 4.1, but for galaxy KIG 503.

KIG 732

Figure 4.12 Same as in Fig 4.1, but for galaxy KIG 732.

KIG 768

Figure 4.13 Same as in Fig 4.1, but for galaxy KIG 768.

KIG 824

Figure 4.14 Same as in Fig 4.1, but for galaxy KIG 824.

KIG 829

Figure 4.15 Same as in Fig 4.1, but for galaxy KIG 829.

KIG 841

Figure 4.16 Same as in Fig 4.1, but for galaxy KIG 841.

KIG 1015

Figure 4.17 Same as in Fig 4.1, but for galaxy KIG 1015.

KIG 1045

Figure 4.18 Same as in Fig 4.1, but for galaxy KIG 1045.

UGG 5705

Figure 4.19 Same as in Fig 4.1, but for galaxy UGC 5705.

UGC 6159

Figure 4.20 Same as in Fig 4.1, but for galaxy UGC 6159.

UGC 6504

Figure 4.21 Same as in Fig 4.1, but for galaxy UGC 6504.

UGC 6810

Figure 4.22 Same as in Fig 4.1, but for galaxy UGC 6810.

UGG 7115

Figure 4.23 Same as in Fig 4.1, but for galaxy UGC 7115.

UGC 7767

Figure 4.24 Same as in Fig 4.1, but for galaxy UGC 7767.

UGC 9070

Figure 4.25 Same as in Fig 4.1, but for galaxy UGC 9070.

UGC 9278

Figure 4.26 Same as in Fig 4.1, but for galaxy UGC 9278.

UGC 10352

Figure 4.27 Same as in Fig 4.1, but for galaxy UGC 10352.

UGC 10599

Figure 4.28 Same as in Fig 4.1, but for galaxy UGC 10599.

HCG 34a

Figure 4.29 Same as in Fig 4.1, but for galaxy HCG 34a.

HCG 37a

Figure 4.30 Same as in Fig 4.1, but for galaxy HCG 37a.

HCG 40a

Figure 4.31 Same as in Fig 4.1, but for galaxy HCG 40a.

HCG 40b

Figure 4.32 Same as in Fig 4.1, but for galaxy HCG 40b.

HCG 61a

Figure 4.33 Same as in Fig 4.1, but for galaxy HCG 61a.

HCG 68a

Figure 4.34 Same as in Fig 4.1, but for galaxy HCG 68a.

HCG 68b

Figure 4.35 Same as in Fig 4.1, but for galaxy HCG 68b.

HCG 68d

Figure 4.36 Same as in Fig 4.1, but for galaxy HCG 68d.

HCG 82a

Figure 4.37 Same as in Fig 4.1, but for galaxy HCG 82a.

HCG 93a

Figure 4.38 Same as in Fig 4.1, but for galaxy HCG 93a.

NCG 759

Figure 4.39 Same as in Fig 4.1, but for galaxy NGC 759.

NGC 807

Figure 4.40 Same as in Fig 4.1, but for galaxy NGC 807.

NGC 2128

Figure 4.41 Same as in Fig 4.1, but for galaxy NGC 2128.

NGC 2320

Figure 4.42 Same as in Fig 4.1, but for galaxy NGC 2320.

UCG 2534

Figure 4.43 Same as in Fig 4.1, but for galaxy NGC 2534.

NGC 2672

Figure 4.44 Same as in Fig 4.1, but for galaxy NGC 2672.

NGC 2768

Figure 4.45 Same as in Fig 4.1, but for galaxy NGC 2768.

NGC 2810

Figure 4.46 Same as in Fig 4.1, but for galaxy NGC 2810.

NGC 3656

Figure 4.47 Same as in Fig 4.1, but for galaxy NGC 3656.

NGC 3928

Figure 4.48 Same as in Fig 4.1, but for galaxy NGC 3928.

NGC 4692

Figure 4.49 Same as in Fig 4.1, but for galaxy NGC 4692.

NGG 5666

Figure 4.50 Same as in Fig 4.1, but for galaxy NGC 5666.

NGC 6702

Figure 4.51 Same as in Fig 4.1, but for galaxy NGC 6702.

NGC 7330

Figure 4.52 Same as in Fig 4.1, but for galaxy NGC 7330.

CHAPTER 5

GALAXY EVOLUTION OUTSIDE OF CLUSTERS

5.1. Morphological study of the Catalog of Isolated Galaxies of Karachentseva

In the initial phase of this thesis, the main purpose was to study the interstellar medium of isolated early-type galaxies. However, it was quite apparent that very little work had been done on galaxies in this kind of environment. For this reason, it was expected that other galaxy properties could turn out to be important as well. The first objective was to find a list of suitable isolated galaxies to study. It was realized that Karachentseva's KIG catalog would be adequate for the selection of the sample. Galaxies classified as early-type in that catalog were selected, and a program for their observations was undertaken. *B* and *I* broad band optical images were obtained at the Steward Observatory 90 inch telescope, as well as *K_s* band infrared images at either the 90 inch or the 61 inch telescopes. At the beginning it was expected (and even hoped) that all the galaxies in the sample would turn out to be true early-types. But soon, it was realized that this was not going to be the case. From the visual inspection of the galaxies obtained at the telescopes, there was no other choice but to start discarding those galaxies that

appeared to have later galaxy types. The final result was that the list of bona fide isolated early-type galaxies became very short. Most of the misclassified galaxies turned out to be spirals, but an important component due to merger candidates or at least perturbed galaxies was also found. At that point it was realized, that a statistical study of the morphology of isolated galaxies could be interesting in its own right. The results obtained from this study turn out to be important, because they provide important new clues about the evolution of isolated galaxies.

5.1.1. Statistical Results from the observations of galaxies in the KIG

Overall, 38 galaxies from the KIG catalog were observed. The morphological classifications assigned by this work are based on the direct and residual images shown in Appendix A. Previous morphological classifications and other comments for individual galaxies are presented in Appendix B. The number of galaxies in the sample is not large enough to provide reliable statistical information about minor differences in the morphological classifications. For this reason, the main focus of the morphological study is instead, to achieve a good assessment of the numbers of early-type and late-type galaxies, with which to answer the basic question: Among the 1051 galaxies in the KIG, what percentage of them is represented by isolated elliptical galaxies? It is hoped that by answering this question, a preliminary answer can be obtained to the more important question: What is the percentage of ellipticals in isolated regions of space? A definitive answer to this question will only be possible with further studies with a much larger, complete sample of galaxies.

Several immediate results can be obtained from a simple analysis of the morphology of these galaxies. Assuming that the morphological misclassification happens in only one direction, i.e., that spirals are sometimes classified as ellipticals in Palomar plates (due to saturation, poor resolution, or any other reason), but

that ellipticals are only rarely classified as spirals, the following conclusion can be drawn. From a total of 30 galaxies classified as ellipticals in our sub-sample of the KIG, at least 15 galaxies were found to be misclassified. This gives a misclassification rate of 50%. Since the percentage of ellipticals in the KIG catalog was 11%, the true percentage of ellipticals should be $\sim 6\%$. It would be desirable to estimate an error value to the percentage of ellipticals. Unfortunately, the number of ellipticals investigated here includes just $\sim 25\%$ of the total number of these galaxies in the KIG. Furthermore, there is no straightforward way to estimate the error using a formalism like K-S. We can at least find an upper limit to the percentage of ellipticals, by considering the extreme case, that the only misclassified ellipticals in the KIG are the 15 found in our subsample. In this situation, an upper limit of $(95/1054) \times 100 = 9\%$ can be set. But this extreme case appears to be unlikely. According to counting statistics, the error should be $\sim 1\%$ in the fraction of ellipticals. Conservatively speaking the fraction of elliptical in the KIG should be about $(6 \pm 2)\%$.

Among the galaxies classified as ellipticals in the KIG, there are some that present obvious spiral features. However, there is also a small but significant component of galaxies with faint but clear spiral features. None of these spiral features were clearly detectable in the Palomar plates, and for that reason they were considered to be ellipticals by Karachentseva and other investigators. It is important to add, that the galaxies with faint spiral features are not considered as misclassified in the previous exercise, so that the $\sim 6\%$ determined above appears to be even more realistic. The percentage of S0's is already very low in the KIG (in the $2 - 4\%$ range). Therefore, the percentage of isolated early-type galaxies in the KIG should be $\sim 10\%$. In the present study it is found that the number of spirals may account for $\sim 85\%$ of the galaxies in the KIG, rather than the $\sim 82\%$

considered by Karachentseva. The slight change in the percentage of spirals may not be very relevant in itself. What is important, is the substantial decrease in the percentage of elliptical galaxies. For completeness, Irr galaxies represent $\sim 3\%$ of the KIG. Studies of nearby field galaxies (Sandage and Tamman 1979, and Dressler et al 1980) have reported $\sim 80\%$ S+I, $\sim 10\%$ S0, and $\sim 10\%$ E. The percentages of ellipticals and S0 galaxies found in the KIG are roughly 50% of those numbers. Although we cannot rule out the possibility of bad statistics at the present time, this difference might be a real environmental effect. Wirth (1983), in his study of galaxies at low density has found that in regions of moderate density, it is possible to find ellipticals in pairs or in groups, but that it is rare to encounter a single elliptical. Perhaps the low percentage of ellipticals in the KIG is a manifestation of Wirth's result.

5.1.2. Candidate Mergers in the Early-Types Sample in the KIG

One of the most intriguing results of the present work is the relatively large number of merger candidates or at least perturbed galaxies that have been found among the so called early-type galaxies in the Karachentseva sample. They are identified as such, mainly from the resemblance of some of the features in the images presented in Appendix A, with those that are commonly associated with mergers: shells, tidal tails, multiple nuclei, perturbed morphologies, and far infrared luminosity (IRAS detection). This scheme for identifying candidate mergers is widely used in the literature (see for instance, Le Fevre et al. 2000). According to this prescription, the objects that are considered as merger candidates are the following.

KIG 768. This galaxy bears a close resemblance with NGC 3656, which is a well known case of a merger (Balcells & Stanford 1990). It presents shells and possible tidal tails. It was detected by IRAS at $60\ \mu\text{m}$ and at $100\ \mu\text{m}$. As for most galaxies

in this list, no follow up study has been published.

KIG 894. The morphology of this galaxy looks like a number 8. It has two interlaced rings with two bright knots at the opposite ends of the “8” in the *B* image. The central region of the galaxy is not as bright as the knots in the *B* band, but it is comparable in brightness in the *I* band. If the knots correspond to the nuclei of two galaxies, the image suggests that they are involved in a fast merger process. Some of the morphological differences between the *B* and *I* images are very likely due to dust extinction. In fact, this galaxy was detected by IRAS at $25\ \mu\text{m}$, $60\ \mu\text{m}$ and at $100\ \mu\text{m}$. However, the complete loops in the “8” rule out the possibility that this is simply a very dusty barred galaxy.

KIG 503. presents a fairly smooth light distribution in the outer regions of the galaxy. The central region, however, presents two nuclei that are clearly visible in the image. The presence of double nuclei is often given as evidence for merger activity (Forbes & Hau 2000). This galaxy has also been detected by IRAS.

KIG 74, KIG 248, KIG 829. These galaxies are highly asymmetrical, which is also considered as a possible indication of merger activity. Besides, the images of these galaxies resemble those that have been obtained by theoretical simulations by Weil. KIG 248 and KIG 829 were detected at all wavelengths by IRAS. KIG 74 was detected at $60\ \mu\text{m}$ and $100\ \mu\text{m}$.

KIG 1042. This galaxy presents shells, which are usually taken as indicative of a merger event in its past.

KIG 1015. This is a highly perturbed galaxy, for which merger activity is not ruled out.

Thus, the total number of merger candidates in the KIG sample might be as

large as 8 galaxies. All of these galaxies were classified as ellipticals in the KIG, and all but the last two galaxies in the list were detected by IRAS. None of the merger candidates and perturbed early-types found in the KIG sample have been studied in detail up to now, and we would like to study them in the near future. They could be excellent targets for HST, SIRTf, as well as other ground and space facilities. High resolution images could reveal regions of intense star formation, dust distributions, globular clusters ages, etc. Such information would be very valuable for a better understanding of the connection between mergers and isolated elliptical galaxies. Likewise, x-ray images could provide information of the history of the groups from which these galaxies presumably originated. The feasibility of studying the fossil remnants of poor groups via their x-ray emission has been successfully demonstrated by Ponman et al. (1994), Mulchaey and Zabludoff (1999), Vikhlinin (1999) and Jones et al. (2000).

5.1.3. Evolution of Mergers into Isolated Early-type Galaxies

Setting aside questions about the completeness of the sample, small number statistics, and other possible biases it would be possible to answer some questions about the evolution of mergers. The knowledge of the present number of mergers (N_M) in combination with the present number of isolated ellipticals (N_E) in the same sample can be used to find the merger rate R_M , which is defined as the number of mergers that become ellipticals per unit time. The present number of ellipticals is given by $N_E(T) = R_M N_M T$. Assuming the values found for the KIG sample, $N_E(T_H) = 15$, and $N_M = 3$, the merger rate is $R_M = N_E/(N_M T_H) = 5/T_H$. Which implies a merger life time of $\sim 3Gyr$. Since the mergers originate from compact groups (in a very broad sense, including 2 or more members), N_M should be equal to the number of compact groups. If this is the case, the time it takes a

compact group to become a single elliptical should be larger than $\sim 3\text{Gyr}$. This result is *roughly* consistent with many observational and theoretical investigations of the evolution of compact groups into single elliptical galaxies. From a study of the range in optical colors as well as the fraction of elliptical galaxies in compact groups, Zepf and Whitmore (1991) found that it takes at least 4 Gyr for such evolution. The results of numerical simulations by Barnes (1989, 1990), Weil and Hernquist (1996), and Mihos (1999), have found that it takes 1Gyr or longer for the merging of compact group into ellipticals. As we will discuss shortly the exact value of the life time is very important to see if our results are consistent with these models. On the other hand, the evolution models of Athanassoula et al. (1997) predict longer lifetimes for the evolution of groups, in some cases longer than the Hubble time. The slowing down in the merger rate is attributed to the distribution of mass in a common halo in the group. Observational evidence for this mass has been found by Zabludoff and Mulchaey (1998).

The question can be inverted, and ask how many isolated elliptical galaxies would be expected to exist assuming the merger life time T_L is known. There is not a unique value for T_L . For the purpose of this work, let us assume a fast evolution model with $T_L = 1.0$ Gyr. In this case, the expected number of isolated ellipticals would be 45, which is 3 times larger than the number of ellipticals in our sample. The merger lifetime is a very critical quantity. If it is significantly smaller than 1Gyr, there is a problem of overproduction of ellipticals.

While evidence for the merger hypothesis has been found in this work due to the significant number of mergers that are observed, there might be a problem of over-production of ellipticals if the merger lifetime is shorter than 1 Gyr. This conflict can be solved by assuming that the elliptical morphology is not the final

stage in the evolution of many isolated galaxies. As has been pointed out by Kauffman (1995), early-type galaxies can collect matter from the intergalactic medium and could be able to form new disks, and eventually become spiral galaxies. In this way, fast evolutionary models could explain the high percentage of mergers, whereas the one by Kauffman would be able to explain the low percentage of isolated ellipticals.

Slow models like the one by Athanassoula et al. (1997), have no problem explaining the low percentage of isolated ellipticals. But they could not account for the high percentage of mergers either. Although there is no agreement on how long merger signatures are detectable, it is unlikely that they can survive for a Hubble time (Mihos & Hernquist 1994, Mihos 1995). For this reason, extremely slow evolutionary models can be ruled out for the isolated environments studied in this thesis. It is also important to appreciate that the model by Athanassoula et al. (1997) depends on the mass distribution of each group. Different conditions might be operating in nature. In this regard, as shown by Zabludoff and Mulchaey (1998), the evolution of poor groups appears to be slow, however, it is possible that at least in some isolated compact groups this evolution occurs much faster.

There may be another line of evidence that tends to support the conclusion that isolated early-type galaxies continue evolving. Is it possible that the spirals with faint arms seen in this work really represent a population of galaxies that are in the transition between ellipticals and spirals? The galaxies with faint arms found in this work include: KIG 179, KIG 393, KIG 505, KIG 511, KIG 537 and KIG 798. It would be very interesting to know if faint spiral arms are also seen among cluster ellipticals. The answer to this question would be interesting in two aspects. First it would tell us whether such features are unique to isolated ellipticals (which

could support the argument of post-merger evolution of isolated ellipticals), or that there is more structure than we think in cluster ellipticals. As far as we are aware, no statistical study of faint spiral arms in any kind of ellipticals have been reported.

5.2. Study of the Light Profile of the galaxies

To study the light profile of the galaxies in the samples, the surface brightness profiles have been fitted with the $r^{1/n}$ law, originally introduced by Sersic (1968). The expression for the Sersic function is given by:

$$I(r) = I_e \exp[-b_n[(r/r_e)^{1/n} - 1]].$$

In this expression the Sersic index n (also referred to as the structure parameter) is a free parameter that provides the best fit to the data. It can be readily seen that this expression has the same form as the de Vaucouleurs law. In fact, for $n=4$ the Sersic profile becomes the de Vaucouleurs function, with $b_4 = 7.67$. I_e is the intensity at r_e , and as in the de Vaucouleurs law, the scale radius r_e is defined so that half of the light of the galaxy is enclosed within this radius. This requirement determines the parameter b_n , which turns out to be a function of n . For this work $b_n = 2n - 0.327$, which is considered to be a good approximation to b_n proposed by Capaccioli (1989). The Sersic profile fitting also includes the exponential profile, which is typical of galaxy disk profiles, when $n = 1$. The generality of the Sersic function over the de Vaucouleurs $r^{1/4}$ and the exponential profiles has several advantages, that can be used to study the light profile of galaxies.

Aside from the advantages of a more general approach to fitting the light profiles, the use of Sersic profiles has proved to be fruitful, because several interesting correlations have been found between the Sersic parameters and galactic properties such as the absolute magnitude and the size of galaxies. Young and

Currie (1994) fitted Sersic profiles to a sample of dwarf elliptical galaxies and found that the Sersic index is correlated with the absolute magnitude. They found that the fainter galaxies usually have smaller values of the Sersic index n . Ryden et al. (1999), studying a sample of dwarf S0 and dwarf elliptical galaxies in the Virgo cluster, found that the structure parameter n peaks close to $n = 1$ (exponential profile). A similar correlation had also been found by Davies et al. (1988) in their study of low surface brightness dwarf elliptical and spheroidal galaxies in the Fornax cluster. They found that n is correlated with the logarithm of the scale radius r_e . Caon et al. (1993) studied a volume limited sample of elliptical and S0 galaxies in the Virgo cluster, and they found that ordinary cluster early-type galaxies obey the same correlation. More recently, Andrekakis et al (1995), and Courteau et al (1996) also found this trend for the bulges of spiral galaxies. Graham et al (1996), using data for a complete sample of bright cluster galaxies (BCGs) out to $15,000 \text{ km s}^{-1}$, extended Caon et al.'s work by showing that the same correlation between the structure parameter n and the scale radius is found among the BCGs. In summary, these studies have found that a correlation between n and $\log(r_e)$ is valid for a wide variety of galaxies. It appears that Sersic indexes < 4.0 , prevail among dwarf ellipticals, whereas $n > 4$ is typical of bright cluster galaxies.

5.2.1. Method for Finding the Sersic Parameters

A straightforward procedure to fit the data with a Sersic profile can be obtained, by taking the natural logarithm of the expression for the Sersic function given above. The equation that results is:

$$\ln[I(r)] = [\ln(I_e) + b_n] + [-b_n/r_e^{1/n}]r^{1/n}.$$

By defining $x = r^{1/n}$, and $y = \ln[I(r)]$, this equation becomes a straight line of the form $y = A + Bx$. The procedure consists in varying the parameter n over a wide range of values. For each value of n , the best linear fit to the data is obtained by using the method of least squares, and a χ^2 value is calculated. The parameter n , and the A and B coefficients that produce the minimum χ^2 are the ones that give the best fit to the data. Once these parameters are known, all the Sersic parameters can be easily determined. Namely, the scale parameter is given by

$$r_e = (-b_n/B)^n,$$

whereas the effective intensity is given by:

$$I_e = \exp[A - b_n],$$

where $b_n = 2n - 0.327$ as defined above. To normalize the results for the surface brightness magnitude and the effective radius, a physical scale in kiloparsecs has been adopted. Hence, r_e is measured in kpc, and μ_e is measured in $\text{mag}/(\text{kpc})^2$.

Before examining the fits to the profiles, it is important to discuss some of the errors in the data that are likely to affect the determination of the Sersic parameters. At small galactic radii, the main problems are due to bad seeing, tracking errors, and to errors in the photometric calibration (for this work the last problem is important, due to the non-photometric nature of several of the galaxies), as well as by errors due to seeing. At large radii, the data is increasingly dominated by sky-subtraction errors.

To avoid some of the problems at small radii, the core region have been excluded from the analysis. To minimize the contributions of the core, only data outside the $r=3$ arcsec radius are considered in the fit. This is the same inner cutoff that was chosen by Graham et al (1996). Caon et al. (1993) consider data

outside “a few arc sec” (without further definition), which in principle should also be comparable to the range in this work, so that it will be meaningful to make comparisons with their work. Since the main problems with the data at large radii are due to sky subtraction errors, the sky subtraction error was varied over a wide range, from 0% to 2% of the sky assumed value. Regarding this point, it is important to mention two things. First, the real sky subtraction error is clearly contained within this range, because this value is typically 0.5% of the sky value, and generally lower than 1%. However, the presence of unwanted reflections by bright objects is not uncommon, and by allowing a variation of the sky by at least $1.0 \times \sigma$ a more realistic value for the uncertainty of the sky subtraction is obtained. Second, the variation of the sky subtraction error primarily affects the error values at large galactic radii, where the data have a lower signal to noise ratio. Obtaining all possible solutions in (n, I_e, r_e) space within the sky subtraction error range specified above, permits to find an average value for each of the parameters, as well as the respective errors. The errors are determined in such a way, that all possible solutions are contained within the error bracket. The determination of error bars might be regarded as conservative. However, the method works because in most cases the parameters are well constrained within a small range and the error bars do not turn out to be excessively large. A somewhat similar procedure was adopted by Ryden et al (1999).

5.2.2. Results from the Sersic Profile Fits

The profiles have been fitted to the semi-major axes of galaxies in the 4 samples, for both the B and I optical bands. The results for the Sersic parameters are presented in Table 5.1, and the fits are drawn in the plots for the surface brightness profiles in Figures 3.1 - 3.48. In the fits shown, a sky subtraction error of 0.5%

of the sky value has been assumed. In most cases the fits are quite good. There are some galaxies, however, that are not well fitted by the Sersic profile. The most pathological case is NGC 5666 that has a very flat brightness profile that extends to ~ 8 arc sec, due to the presence of several bright knots in the region close to the nucleus (see image in Appendix A). For the rest of the cases with bad Sersic fits, the failure occurs either at large galactic radius or in a periodic fashion. Bad sky subtraction could account for some of the discrepancies at large radius. But, for instance, NGC 7330 (Fig.3.48) appears to have another component. The fitted profile underestimates the brightness of the galaxy outside the 20 arc sec semi-major isophote. Several galaxies are not well fitted by the Sersic profile due to the presence of spiral arm features. KIG 83 (Fig. 3.1), KIG 120 (Fig. 3.3), KIG 503 (Fig. 3.8), KIG 841 (Fig. 3.12), and NGC 807 (Fig 3.39).

Once the Sersic parameters are known for the B and I optical bands, it is possible to test whether there is a wavelength dependence. The second and fifth columns of Table 5.1, present the results for n_B and n_I (the Sersic indexes for the B and I data). These values have been plotted in the top panel of Fig. 5.1, with the purpose of comparing the results for the two bands. The line shown in the upper panel is the best fit to the data and is given by $n_I = 0.16 + 1.05 n_B$, with a correlation coefficient of 0.90. Likewise, the bottom panel of Fig. 5.1 presents r_B as a function of r_I , and the best fit line is given by $r_I = .06 + 0.95 r_B$, with a correlation coefficient of 0.97. The slopes of the best fit lines in these two plots differ from 1.0 by only $\sim 5\%$. This means that for most galaxies the Sersic parameters obtained at the B and I bands are very close. There are some cases, however, where these numbers differ considerably. One such case is galaxy NGC 2768, where $n_B = 3.5 \pm 0.2$, whereas $n_I = 5.1 \pm 0.1$. Since this galaxy is known to have dust, it is possible that at least in part, the discrepancy

is due to dust structures in that galaxy. The conclusion of this exercise, is that unless dust significantly distorts the galaxy isophotes, the Sersic parameters are very similar at different optical wavelengths. The good agreement between the r_e parameters at different wavelengths and the range of values of the results appear to be physically meaningful (lacking extremely large or extremely small radius). These considerations suggest that the Sersic radius might be a good parameter to characterize the size of galaxies.

Due to the wide range of apparent magnitudes of the galaxies studied in this work, it is important to test if there is a possible bias toward lower or higher n values for the fainter galaxies. A bias like this may occur whenever the sky starts to dominate the outer regions of the galaxies. To answer this question, the apparent magnitude B_T (see Tables 2.1 - 2.4) of the galaxy has been plotted as a function of the n Sersic parameter in Fig. 5.2. The best fit line is also presented in the figure. As can be seen in this plot, n is not correlated to B_T . This is manifested by the correlation coefficient of the best fit which is equal to 0.06. Therefore, the bias indicated above does not seem to be of serious consequences for the B and I optical data. But it could represent a real problem for the K_S data, due to the lower signal to noise in the outer regions of the galaxies. For this reason the infrared data are not considered here for the discussion of the Sersic profiles.

The top left panel of Figure 5.3 presents a histogram of the distribution of galaxies in the KIG as a function of n . Although there are four galaxies from the KIG sample that have n between 3 and 4, it is somewhat surprising that only one of the galaxies (KIG 841, which is not elliptical but a floccular spiral!) from that sample obeys a de Vaucouleurs $\tau^{1/4}$ law. From the galaxies in the other three samples, there is only a handful that are consistent with the $\tau^{1/4}$ law. These include

two galaxies from the Fasano and Bonoli sample (UGC 9070 and UGC 9278), one galaxy from the HCG (HCG 68b), and two galaxies from the ISM selected sample (NGC 4692 and NGC 2320). There are a few other galaxies (NGC 759, and NGC 807) that are marginally consistent with the $r^{1/4}$ law. These results are not unusual, however. Departures from the $r^{1/4}$ law have been found by most studies of galaxies with the Sersic profile function. The bottom panels of Figure 5.3 present the results of the studies by Caon et al. (1993) and Graham et al. (1996). On the average, however, the galaxies studied here are not too far from $n = 4$. This can be seen on the second column of Table 5.7, where the average and standard deviation of n for each of the samples are presented. The value of n for the FB sample appears high, but this is in part due to galaxy NGC 7767 with $n=14.5$.

Following Graham et al. (1996), no cases with $n > 15$ are considered in this work. For those galaxies, better fits can be obtained with power law profiles. Graham et al. (1996) found that 40% of the galaxies they studied had $n > 15$. They attribute this high percentage to the fact that their sample consists of some of the brightest galaxies in clusters, and to their expectation of a significant number of galaxies with large n due to the correlation they found between n and $\log r_e$. In this work, the percentage of galaxies with $n > 15$ is less than 10%. Likewise, this study does not find the large percentage of galaxies with small n values that cluster around $n = 1$ in the Ryden et al. (1999) study of dwarf galaxies. Most of the values for n in our samples considered in this work are spread over a range of values between 1.0 and 9.0. The distributions of the Sersic parameter n in the KIG (top left panel in Fig. 5.3), is not significantly different from that in which our 4 samples are included (top right panel). Due to the diversity of the samples, a similar distribution among the samples would indicate that the galactic environment or the presence of an ISM, are not the primary factors in the determination of the n Sersic

parameter. Due to the small number of galaxies in the samples, however, such a claim cannot be made from this comparison. The lower 2 panels of Fig. 5.3 present a comparison of the Sersic parameter n distribution for cluster environments. Notable differences can be seen in this distribution. In the Caon et al. (1993) sample most galaxies are in the range between $n=1.5$ and $n=3.5$, and a significant drop in the number of galaxies as a function of n is observed. The KIG sample presents a uniform distribution between $n=1$ and $n=7$. The Graham et al. (1996) sample includes galaxies with a wide range of n values, with a maximum at $n \sim 5$ and a long tail that extends to the very large values of n .

Fig. 5.4 presents a similar comparison between the galaxy distributions, but now as a function of the logarithm of the Sersic effective radius r_e . The Caon et al. (1993) sample has the highest percentage of galaxies with small r_e . The KIG does not have any galaxy in the bin where the Caon et al. (1993) data have their maximum number of galaxies, but it overlaps with their largest r_e , as well as with the small radius range of Graham et al. (1996). The bin with the most galaxies of Graham et al. occurs at a radius of $\sim 10kpc$, however, it has a considerable number of galaxies with r_e of several hundred kpc, and even one that exceeds 1 Mpc. Although the Graham et al. sample includes several CD galaxies, some of their values appear to be unphysical. At a first glance, the results of the n distribution comparison shown in Fig. 5.3 suggest different behaviors for different environments. The fact that such behavior is so similar to the one exhibited by the r_e distribution in Fig. 5.4, argues that these effects are simply due to the size of the galaxies rather than the environment. Similar conclusions were found and discussed by Graham et al. (1996) in their study of the brightest galaxies in clusters. A simple extrapolation of the results of Ryden et al. (1999), and of Graham et al. (1996), suggests that the range of values of n observed in this work

can be understood in terms of the intermediate size and absolute magnitude of the galaxies studied in this thesis. In view of the great difference in properties of galaxies with different luminosities, it is important to compare the absolute magnitudes and color distributions for the different samples. Table 5.4 presents a comparison of the absolute magnitude M_B and the color index $(B-I)$ for the 4 (KIG, FB, HCG, and ISM selected) samples studied in this work and for those of Goudfrooij (1994) and Caon et al. (1993). Since there is significant overlap in the distributions of absolute magnitudes and colors for the galaxies in the 4 samples (see also Fig 3.49), it is meaningful to make comparisons between their properties. The absolute magnitude of the Caon et al. (1993) sample (19.04 ± 1.5) is a little fainter than for the galaxies in this work. Because of the large scatter in the Caon et al. absolute magnitude, however, there is a significant overlap in these values between their sample and the samples in this work (particularly with the F&B and KIG samples). The absolute magnitudes of the Graham et al. data are not shown, but their galaxies are much brighter than the ones from this work, because they were selected among the brightest galaxies in clusters.

Possible correlations among the Sersic parameters themselves, and with other galaxy properties have been searched for in this work. Figure 5.5 presents a plot of $\log(n)$ vs. $\log(r_e)$ for the B band. The values and error bars used in these plots were extracted from Table 5.1. Except for the large scatter in the KIG data, there is a clear correlation between $\log(n)$ and $\log(r_e)$. Thus we confirm the validity of this relation for the galaxies in this thesis. In order to compare with previous results that overlap in absolute magnitude, a plot of $\log(n_I)$ as a function of $\log(r_I)$ including the 4 samples is presented in Fig 5.6. In the same plot, the results of Caon et al. (1993) and those of Graham et al. (1996) have also been included. The solid line $\log(n)=0.28+0.52\log(r_e)$ is the best fit found by Caon et al. (1993), and

is shown here to compare with our data. The agreement is acceptable considering the scattering in the data. The scatter in the results of Graham et al. is somewhat higher, but shows the same general trend. Caon et al. (1993) also compared the results with the study of the LSB dwarf elliptical and spheroidal galaxies in Davis et al. (1988), showing that the $\log(n)$ vs. $\log(r_e)$ correlation is also valid for fainter galaxies. Although there is no clear explanation for the scatter in Graham et al. (1996) data, we know that the scatter in our data is mainly due to the KIG data. Since the KIG contains several galaxies with spiral structure and other morphological features, the scatter is likely due to such features.

5.3. Global Parameters of the Objects in the Thesis

With the purpose of studying possible differences between the objects in the four samples considered here, and in order to be able to compare with the results of other investigations, we have calculated parameters that are representative of the properties of the galaxies. Table 5.2 presents a summary of the structural and morphological properties of the galaxies in this study. The assessment of these properties is based on either the results of surface photometry, or from visual information obtained directly from the images in Appendix A. Comments and relevant information about individual objects are given in Appendix B. Table 5.2 also presents the average color index ($B-I$), along with its logarithmic gradient. Among the galaxies for which B and I data are available, all the HCG galaxies present negative color gradients, and all but one of the galaxies in the ISM selected sample have negative gradients. In fact negative gradients have been found for all the featureless ellipticals. Among the isolated galaxies, however, the number of galaxies with positive gradients that has been found is significant. In the Fasano and Bonoli sample there are 3 galaxies with positive gradients. UGC 6810, UGC

5705, and U10352. UGC 6810 was taken under very bad seeing ($2.3''$) and the gradient is very small, so it could be spurious. UGC 5705 is a perturbed galaxy rich in ISM (see the residual image in Appendix B), and UGC 10352 is also contain to contain an ISM. For the KIG, 7 negative and 5 positive gradients were found. The later include: KIG 393, KIG 503, KIG 768, KIG 841, and KIG 1015. All but KIG 393 are in our list for candidate mergers. Furthermore, KIG 393 was detected by IRAS and it has and spiral arm close to the nucleus (see Appendix A). Mihos & Hernquist (1994) have found that merger-induced starbursts that have solar metallicity, should be detectable as a blueing of the nuclear region for several Gyr. This effect is very likely what has been seen recently by Menanteau et al. (1999) and by Ellis et al. (2000) in field ellipticals at large redshift. It would be interesting to know if some of the KIG galaxies are local representatives of that population. In Table 5.3, average values for the ellipticity and the position angle with the respective standard deviations are presented. This table includes the results for the three different wavelengths for which surface photometry data was obtained. In the context of this discussion, the standard deviation is not necessarily a measure of an error value, but rather, an indication of the behavior of the parameters as a function of radius. For instance, a large standard deviation in P.A. implies that a galaxy have large isophotal shifts. The agreement between the parameters at different wavelengths is quite good, particularly considering that discrepancies are expected to occur due to the dusty nature of many of these objects.

5.3.1. High order Residual Terms

Following Bender et al. (1989), Peletier et al. (1990), and Goudfrooij (1994), the so called “characteristic” values of the higher order terms have been measured. To obtain these, the average and standard deviation of the three minimum or

maximum values in the radial profiles of the Fourier coefficients given in chapters 3 and 4 were used. These numbers were then multiplied by 100 in accord with the definition in the references above. Likewise, the nomenclature adopted here is the same as that used in those references. For instance, S_4 is the coefficient of $\sin(4\theta)$, and C_3 is the coefficient of the $\cos(3\theta)$ term. It has been known for several years that the isophote shapes are related to various galaxy properties (Bender et al. 1989). The importance of the characteristic values is that these are the parameters commonly used for extracting such information. It has been suggested, for instance that the third order coefficients are due to dust features, and that the C_4 coefficients are due to structural features of the galaxies. Using the surface photometry results from chapters 3 and 4 these assertions will be tested. The characteristic values for the B data are presented in Table 5.5, and those for the I data are given in Table 5.6. If the interpretations of the harmonic amplitudes are correct, then they can be used as a tool to learn about the properties of the galaxies in this thesis.

Let us start by studying the third order coefficients. The left top panel on Fig. 5.7 presents the plot of $S3_I$ as a function of $S3_B$ for all the galaxies in the four samples for which B and I data were observed. The line $S3_I = -0.08 + 0.52 S3_B$ is the best fit to the data, with a correlation coefficient of $r = 0.88$. The fact that the $S3_I$ characteristic values are smaller than the $S3_B$ is consistent with the interpretation that the features in the $S3$ coefficient are mainly due to dust. This is so, because the stellar extinction by dust is smaller at the I -band than at the B -band. If this interpretation is correct, it is also expected that such features should be even smaller at longer wavelengths. One of the main reasons for obtaining the K_S data was to be able to reduce the effects of dust extinction in this study. However, due to the lower S/N in the outer regions of the galaxies at

K_S (as compared with the optical CCD data), the K_S data cover a smaller range in galactic radius. For this reason, the characteristic values at K_S were obtained for only a fraction of the galaxies. Fortunately, this fraction includes some of the galaxies that are more dusty in this thesis. Therefore, they are very useful for this work. Taking advantage of the K_S data, the relation between $S3_{K_S}$ and $S3_B$ is presented on the top right panel of Fig. 5.7. The best fit line is given by the equation $S3_{K_S} = -0.14 + 0.01 S3_B$. In other words $S3_{K_S} \sim 0.0$, which means that the effect of extinction is almost negligible at $2.3 \mu\text{m}$ wavelength. The same analysis has been applied to the characteristic values of $C3$. The $C3_I$ vs. $C3_B$ relation is presented at the bottom left panel, while the bottom right panel shows the $C3_{K_S}$ vs. $C3_B$ relation. The results for the $C3$ coefficients, are very similar to the ones described above for the $S3$ coefficients. The best fit line for the $C3_I$ vs. $C3_B$ is $C3_I = 0.05 + 0.54 C3_B$. Perhaps fortuitously, this slope differs by less than 5% from the slope of the $S3_I$ vs. $S3_B$ relation. The best fit line for the $C3_{K_S}$ vs. $C3_B$ is $C3_{K_S} = 0.25 - 0.0156 S3_B$. The summary of the results for the third order coefficients presented here indicates that the third order Fourier coefficients are indeed due to dust-features in the galaxies.

The behavior of the fourth order coefficients is presented in Fig. 5.8. The relation between $S4_I$ and $S4_B$ is presented on the top left panel, and the best fit line is $S4_I = 0.28 + 0.70 S4_B$. On the top right panel the relation between $S4_{K_S}$ and $S4_B$ is presented. The best fit line is $S4_{K_S} = 0.16 + 0.39 S4_B$. The fact that the slope of the infrared line is smaller than that of the I -band fit indicates that the presence of dust appears to play an important role in the interpretation of the $S4$ coefficients. The slope of the best fit line is definitely not zero, however, This implies that besides dust, structural properties in the galaxies may also play a role in the interpretation of the $S4$ coefficients.

The $C4$ coefficients deserve special attention, because they have been claimed by Lauer (1985), Bender & Mollenhoff (1987), Bender et al. (1989) to be associated with the structure of early-type galaxies, namely, whether early-types are disk or boxy. The results for the $C4$ coefficients are shown at the bottom of Fig. 5.8. In contrast to the other harmonic amplitudes, the $C4$ terms do not appear to be strongly dependent on the wavelength. The best line fit for $C4_I$ and $C4_B$ data shown at the bottom left panel is $C4_I = 0.29 + 0.78C4_B$. For the $C4_{K_s}$ vs. $C4_B$ (right panel), the equation of the best fit is $C4_I = 0.44 + 0.71C4_B$ with a correlation coefficient of 0.89. However, there are some outliers that are identified with their galaxy names in Fig. 5.8. These outliers present dusty features. See the plot for C3 on Fig 3.34 for H68a, and Fig 3.42 for NGC 2768. The fact that $|C4_{K_s}| < |C4_B|$, is probably telling us that there are no real disks in these two galaxies. For these reasons, these points should probably be removed from the plot. In any case, the linear relationship found for the $C4$ parameters appears to be strong. The slope for the $C4_\lambda$ vs. $C4_B$ coefficients does not decrease at longer wavelengths as was the case for the other coefficients (in fact it increases its value). This lack of dependence of $C4$ with wavelength means that these coefficients are not primarily due to the presence of dust. By looking at the images in Appendix A, it is possible to verify that the galaxies with a positive coefficient in the coefficient of $\cos(4\theta)$ have disks, whereas those with a negative $C4$ are boxy. Thus, these results confirm the interpretation given by Lauer (1985) and several other works to the $C4$ coefficient.

5.3.2. Comparison of the Global Properties of Early-Type galaxies

Table 5.7 presents a comparison of the galaxy properties found for the 4 samples. The most significant results are found for the galaxies in the KIG sample. These

galaxies have a higher percentage of spiral and disk features, and are more perturbed than the other three samples. As expected, the highest percentage of galaxies with dust signatures is found for the sample of ISM detected galaxies (66% show evidence of dust). However, the percentage of KIG galaxies with dust signatures is also quite high (62%). The highest percentage of boxy galaxies is found for the HCG sample (45 %). In contrast with the KIG sample, except for 2 galaxies (UGC 1503=KIG 83 and UGC 5705), the Fasano and Bonoli sample has been found to be a sample of well behaved elliptical galaxies.

There have been previous studies that report statistical results about the general shape of elliptical galaxies. In a study of a magnitude limited sample of ellipticals in the northern hemisphere Bender et al. (1988) found that $\sim 1/3$ of the galaxies have disk isophotes, $\sim 1/3$ boxy isophotes, and $\sim 1/3$ have isophotes with very small deviations, or irregular isophotes. Rix (1991) found that $1/3$ of the objects in his study have “conspicuous” disks that could be detected at any angle. He also finds that $1/3$ of the objects have “unconspicuous” disks that can only be detected under favorable inclination. Rix (1991) does not give statistics for the galaxies with boxy isophotes but mentions that $1/3$ of the objects are “diskless”, for which the disks are too weak to be seen even if the galaxy is edge-on. For the galaxies in this thesis, the percentages of disk galaxies are all in the 33-66 % range, consistent with the Rix (1991) results. The percentage of boxy galaxies is roughly consistent with Bender et al. (1988), except for the HCG sample, in which case the percentage is 45%.

van Dokkum and Franx (1995) estimate that $78 \pm 16\%$ of early-type galaxies contain nuclear dust. But high resolution is needed to detect it. Sadler and Gerhard (1985) estimated that $\sim 40\%$ of ellipticals contain large-scale dust structures.

They also find that $\sim 50\%$ of the dusty ellipticals are in groups (6-20 members), $\sim 34\%$ are in clusters, $\sim 11\%$ are in pairs, and only $\sim 5\%$ are isolated. Ebner et al. (1988) found that 36% of the ellipticals and 47% of the S0s in the survey of Djorgovsky (1985) are very likely to contain dust. However, in contrast with the results of Sadler and Gerhard (1985), they also find that dusty ellipticals “do seem to prefer low density environments”. Goudfrooij et al. (1994) reported an optical detection rate of 41% of dusty features in their study of ellipticals with $B_T < 12$ in the RSA sample. The results of this study are in general agreement with the results of these workers, except with the finding of Sadler and Gerhard (1985) for isolated early-type galaxies. Our results for this type of galaxies indicate that the percentage of dusty early-types is quite high (see Table 5.7), more in agreement with the results of (Ebner et al. 1988).

We have found a total of 7 galaxies with shells systems from our samples. Two of the galaxies in the KIG have shells. These galaxies are KIG 768 and KIG 1042, and there are no previous reports in the literature for shells in these galaxies. Among the ellipticals in the Hickson compact groups, we have found evidence for shells in 4 galaxies: The shells in HCG 37a, which were previously mentioned by Zepf et al. (1991) were immediately recognized. The shells in the other three HCG galaxies were only recognized after knowing of their possible presence. Two of these galaxies are HCG 10b and HCG 93a, whose shells were first reported by Pildis et al. (1995). They found the shells by studying the residual images of these galaxies. Although the shells appear to be real, some of the features in the residual images of Pildis et al. (1995) are probably spurious (see the comments on HCG 10b in Appendix B on this thesis). The third galaxy is HCG 68d, whose shells were suggested (with a question mark) in the work of Mendes de Oliveira & Hickson (1994). Finally, we observe shells in NGC 3656. The shells of this well studied

merger were discussed by Balcells & Stanford (1990). We regard the evidence for shells in KIG 768, KIG 1042, HCG 37a, and NGC 3656 as strong, while that of HCG 10b, HCG 68d and HCG 93a as somewhat weaker (see Appendix A). Malin and Carter (1983) found that the presence of shells is strongly dependent on the environment, with most of the detections occurring among the isolated or group ellipticals, and only a low percentage among cluster ellipticals. They detected shells in 17% of the isolated ellipticals. Though only two galaxies with shells were found in the KIG sample, this is the number expected ($0.17 \times 15 = 2.5$ ellipticals with shells) from the results of Malin and Carter (1983). The presence of shells is relevant, because they are thought to be produced by mergers (Kormendy and Djorgovsky 1989, Heisler and White 1990, Balcells 1997). The higher probability of finding shells outside of clusters, is indicative of the higher probability of finding mergers in isolated regions.

5.3.3. Summary

From the Sersic profile fits to the surface profiles, a clear correlation between $\log(n)$ and $\log(r_e)$ is found. This correlation is found to be independent of the environment or ISM content of the galaxies, and is in agreement with previous results by Caon et al. (1993) and Graham et al. (1996).

The results of the analysis of the harmonic amplitudes at different wavelengths is consistent with the interpretation advanced by Lauer (1985), Bender and Mollenhoff (1987) and several other investigators, that the third order coefficients (S3 and C3) signal the presence of dust. Likewise, it has been found that the C4 coefficients are mainly related to the overall structure of the galaxy. Using the information obtained from the harmonic amplitudes, as well as other information obtained from the surface photometry and from the inspection of the direct and

residual images in Appendix A, it has been possible to find some of the galaxy properties. This information has been used to compare the properties of the 4 samples. The main result is that isolated ellipticals in the KIG appear to be unique. They are rich in ISM, several of them have positive color gradients and a variety of morphological features (shells, double nuclei, and other merger signatures). Our results for the isolated early-type galaxies, are at odds with the main result of the study done by Fried (1988), where he concluded that the galaxies in the field predominantly have unperturbed morphologies. For his study he analyzed a sample of isolated galaxies from Keel et al. (1985) that does not contain elliptical galaxies. Fried gave two arguments to justify the neglect of ellipticals (because he argues that his result is valid for all morphological types). First he reminds us that the population fraction of ellipticals is only $\sim 10\%$ for low density environments, so that he does not expect his conclusions to change if he includes them. His second argument is that the results of Sadler and Gerhard (1985) did not detect dust lanes or ripples in isolated ellipticals. However the results of Malin and Carter (1983), and those of Ebner et al. (1988) suggest that shells and dust features are more common among isolated ellipticals.

From the morphological study of the KIG it has been found that the percentage of isolated elliptical galaxies in the KIG represents no more than 6% of the total population of galaxies in that sample. This low percentage combined with the high detection rate of merger candidates in the same sample, is used to get a lower limit of 3 billion years for the lifetime of mergers. Assuming that this mergers are due to the evolution of compact groups, This lifetime is roughly consistent with some theoretical models that predict an intermediate lifetime for compact groups. Evolution models that are too slow are inconsistent with these findings, because they cannot explain the relatively large number of mergers. If fast evolution

models (lifetime $< 1\text{Gyr}$) are considered, there is a problem of over-production of elliptical galaxies. This would indicate, that isolated ellipticals probably experience a post-merger evolution that changes their elliptical morphology. This work cannot rule out this possibility. In fact, our finding of several elliptical galaxies with faint spiral arms, probably suggests this alternative. The theoretical work of Kauffman (1995) has also suggested this possibility. But more work is needed to assess these different alternatives. None of the merger candidates found in the KIG were known prior to this work and they deserve further study. Their study could give us insight into the evolution of compact groups into isolated ellipticals.

Table 5.1. Model Parameters for the Sersic Profiles ¹

Galaxy	n_B^2	μ_B^3	r_B^4	n_I^2	μ_I^3	r_I^4
<i>(i) KIG catalog</i>						
KIG 0083	1.0 ± 0.1	24.5 ± 0.1	3.0 ± 0.1	1.1 ± 0.6	22.0 ± 0.1	2.7 ± 0.1
KIG 0089	7.5 ± 0.4	29.4 ± 0.2	13.5 ± 0.5	7.4 ± 0.1	27.1 ± 0.1	11.5 ± 1.0
KIG 0120	7.2 ± 0.8	29.4 ± 0.4	140.0 ± 74^5	...	...	...
KIG 0303	2.5 ± 0.5	26.6 ± 0.6	9.5 ± 3.6	2.7 ± 0.6	23.9 ± 0.6	10.7 ± 4.0
KIG 0358	3.1 ± 0.7	24.5 ± 0.3	2.7 ± 0.3	3.8 ± 1.0	22.5 ± 0.4	2.8 ± 0.5
KIG 0396	5.1 ± 0.5	27.1 ± 0.2	3.3 ± 0.8	4.8 ± 1.0	25.1 ± 0.6	4.8 ± 0.6
KIG 0503	2.7 ± 0.8	26.8 ± 0.1	0.3 ± 0.1	2.6 ± 0.6	25.8 ± 0.1	0.4 ± 0.1
KIG 0732	5.6 ± 0.1	25.3 ± 0.1	6.0 ± 0.1	6.1 ± 0.1	26.8 ± 0.1	6.2 ± 0.1
KIG 0768	...	...	...	1.9 ± 0.2	21.9 ± 0.1	2.4 ± 0.1
KIG 0824	3.6 ± 0.2	24.9 ± 0.1	3.3 ± 0.3	5.0 ± 0.3	22.9 ± 0.1	3.7 ± 0.2
KIG 0841	4.5 ± 1.0	24.7 ± 0.5	7.9 ± 2.0	3.7 ± 0.6	22.5 ± 0.3	5.5 ± 0.7
KIG 1015	5.5 ± 1.5	24.4 ± 0.1	1.6 ± 0.1	...	...	...
KIG 1042	5.7 ± 0.2	26.1 ± 0.1	8.8 ± 0.1	6.4 ± 0.7	24.0 ± 0.4	7.8 ± 1.5
KIG 1045	3.4 ± 0.1	25.9 ± 0.1	7.9 ± 0.1	3.1 ± 0.1	23.0 ± 0.1	5.9 ± 0.2

Table 5.1—Continued

Galaxy	n_B^2	μ_B^3	r_B^4	n_I^2	μ_I^3	r_I^4
<i>(ii) Fassano & Bonoli Sample</i>						
UGC 5705	2.7 ± 1.1	26.9 ± 0.4	0.9 ± 0.1	1.5 ± 0.3	24.6 ± 0.2	0.9 ± 0.1
UGC 6159	7.3 ± 1.5	30.9 ± 0.9	6.4 ± 2.9	8.5 ± 2.3	29.2 ± 1.4	8.5 ± 5.3
UGC 6504	6.4 ± 0.2	25.2 ± 0.1	6.8 ± 0.2	6.7 ± 0.2	22.9 ± 0.1	6.6 ± 0.2
UGC 6810	8.1 ± 0.7	25.4 ± 0.2	6.9 ± 0.5	6.4 ± 0.2	22.7 ± 0.1	5.5 ± 0.1
UGC 7115	14.5 ± 0.6	27.6 ± 0.2	23.1 ± 2.0	...	...	...
UGC 7767	7.1 ± 1.0	29.2 ± 0.2	1.8 ± 0.1	10.1 ± 0.3	27.5 ± 1.0	1.9 ± 0.1
UGC 9070	4.1 ± 0.1	28.8 ± 0.1	3.0 ± 0.1	4.1 ± 0.4	26.6 ± 0.3	2.9 ± 0.3
UGC 9278	4.1 ± 0.4	25.4 ± 0.1	4.9 ± 0.3	4.0 ± 0.1	22.6 ± 0.1	4.4 ± 0.1
<i>(iii) Hickson Compact Groups Sample</i>						
HCG 10b	5.7 ± 0.2	25.1 ± 0.1	7.4 ± 0.4	5.8 ± 0.1	23.2 ± 0.1	7.3 ± 0.1
HCG 37a	6.4 ± 0.1	26.9 ± 0.1	36.0 ± 2.0	7.6 ± 0.1	25.5 ± 0.1	45.5 ± 0.3
HCG 40a	13.7 ± 1.0	28.1 ± 0.2	32.0 ± 0.4	...	...	...
HCG 40b	3.0 ± 0.3	25.2 ± 0.2	5.9 ± 0.4	...	...	...
HCG 61a	2.1 ± 0.5	24.7 ± 0.2	3.3 ± 0.3	...	...	...
HCG 68a	2.1 ± 0.1	25.1 ± 0.1	3.4 ± 0.1	2.3 ± 0.4	23.2 ± 0.4	3.8 ± 0.8
HCG 68b	4.0 ± 1.65	26.6 ± 1.2	7.5 ± 4.0	4.7 ± 0.1	25.0 ± 0.1	8.0 ± 0.2
HCG 68d	1.8 ± 0.1	25.1 ± 0.1	1.6 ± 0.1	2.1 ± 0.2	23.8 ± 0.1	1.6 ± 0.1
HCG 82a	5.1 ± 0.2	24.5 ± 0.2	15.9 ± 0.8	...	...	...
HCG 93a	3.3 ± 1.0	25.7 ± 0.7	10.8 ± 4.1	5.6 ± 0.2	24.6 ± 0.2	17.2 ± 1.0

Table 5.1—Continued

Galaxy	n_B^2	μ_B^3	r_B^4	n_I^2	μ_I^3	r_I^4
<i>(iv) Galaxies Known to Contain an ISM</i>						
NGC 0759	3.7 ± 0.3	25.2 ± 0.2	5.5 ± 0.5	...	...	...
NGC 0807	4.7 ± 1.0	27.1 ± 0.7	14.0 ± 5.0	5.5 ± 1.2	24.3 ± 0.6	12.3 ± 4.3
NGC 2128	1.9 ± 0.1	25.0 ± 1.0	3.1 ± 0.1	...	...	...
NGC 2320	3.9 ± 1.5	26.2 ± 1.0	20.0 ± 11.0	4.0 ± 0.5	22.7 ± 0.4	9.7 ± 1.8
NGC 2768	3.5 ± 0.2	29.2 ± 0.2	11.0 ± 1.0	5.1 ± 0.1	28.1 ± 0.2	25.3 ± 1.7
NGC 2810	7.4 ± 0.2	27.1 ± 0.1	8.0 ± 0.2	7.6 ± 0.1	24.9 ± 0.1	7.7 ± 0.2
NGC 4692	4.0 ± 0.6	24.7 ± 0.3	11.3 ± 1.5	4.1 ± 0.3	22.7 ± 0.2	11.2 ± 0.8
NGC 5666	1.4 ± 0.4	24.2 ± 0.1	0.8 ± 0.1	0.9 ± 0.2	22.7 ± 0.1	0.9 ± 0.1
NGC 7330	3.2 ± 0.3	23.9 ± 0.1	3.7 ± 0.1	...	...	...

¹The Sersic parameters have been obtained by minimizing the χ^2 . The errors were determined allowing for a variation of 1σ in the sky subtraction error value.

²Structure parameter (or Sersic index) n for the B and I filter data.

³Surface brightness in mag kpc^{-2} , evaluated at the effective Sersic radius for the B and I filter data.

⁴Effective Sersic radius in kpc for the B and I data.

⁵This value is too high to be realistic

Table 5.2. Structural and Morphological Summary of the Galaxies ¹

Galaxy	$(B - I)^2$	$\nabla(B - I)^3$	Disky ⁴	Boxy ⁵	Shift ⁶	Dusty ⁷	Spiral ⁸	Pert. ⁹
<i>(i) KIG catalog</i>								
KIG 0083	2.28	-0.35	y	n	3.4	y	y	n
KIG 0089	2.35	-0.08	y	n	0.7	n	n	n
KIG 0120	...	...	n	n	0.5	y	y	n
KIG 0303	1.91	-0.06	y	n	0.3	s	n	n
KIG 0358	1.97	-0.04	y	n	0.7	s	n	n
KIG 0393	1.96	+0.18	y	n	19.6	y	y	y
KIG 0396	2.05	+0.04	n	y	6.1	n	n	n
KIG 0503	1.73	+0.34	y	n	53.5	y	y	y
KIG 0732	2.62	-0.04	n	y	2.8	n	y	n
KIG 0768	...	...	n	n	6.8	y	n	y
KIG 0824	2.25	0.00	y?	n	0.5	y	y	n
KIG 0829	...	...	n	n	24.2	y	n	y
KIG 0841	1.77	+0.07	y	n	1.0	y	y	y
KIG 1015	2.24	+0.22	n	n	6.8	y	n	y
KIG 1042	2.02	-0.18	y	n	3.7	y	n	y
KIG 1045	2.42	-0.12	n	y	0.5	n	n	n

Table 5.2—Continued

Galaxy	$(B - I)^2$	$\nabla(B - I)^3$	Disky ⁴	Boxy ⁵	Shift ⁶	Dusty ⁷	Spiral ⁸	Pert. ⁹
<i>(ii) Fassano & Bonoli Sample</i>								
UGC 5705	1.92	+0.03	y	n	4.7	y	y?	y
UGC 6159	2.07	−0.05	y	n	0.7	n	n	n
UGC 6504	2.17	−0.06	n	n	0.4	n	n	n
UGC 6810	2.25	+0.02	n	n	1.1	y	n	n
UGC 7115	...	...	n	n	1.3	n	n	n
UGC 7681	...	...	n	n		n	n	n
UGC 7767	1.85	−0.29	y	n	20.1	y	n	n
UGC 9070	2.27	−0.02	n	y	1.4	n	n	n
UGC 9278	2.53	−0.08	y	n	0.8	n	n	n
UGC 10352	2.53	+0.08	n	n	2.3	n	n	n
<i>(iii) Hickson Compact Groups Sample</i>								
HGC 10b	2.20	−0.08	y	n	2.2	n	n	n
HGC 34a	...	...	n	n	1.4	n	n	n
HGC 37a	2.02	−0.06	n	y	0.2	y	n	y
HGC 40a	...	...	y	n	0.5	n	n	n
HGC 40b	...	...	n	y	2.5	n	n	n
HGC 61a	...	...	y	n	1.6	y	y	n
HGC 68a	2.10	−0.12	y	n	1.7	n	n	n
HGC 68b	2.03	−0.07	n	y	4.0	y	n	n
HGC 68d	1.34	−0.11	y	n	8.7	n	n	n
HGC 82a	...	...	n	y	0.8	n	n	n
HGC 93a	2.22	−0.10	n	y	3.8	y	n	n

Table 5.2—Continued

Galaxy	$(B - I)^2$	$\nabla(B - I)^3$	Disky ⁴	Boxy ⁵	Shift ⁶	Dusty ⁷	Spiral ⁸	Pert. ⁹
<i>(iv) Galaxies Known to Contain an ISM</i>								
NGC 759	...	...	n	n	4.0	n	n	n
NGC 807	2.47	-0.24	y	n	0.6	y	y	n
NGC 2128	...	...	y	n	2.8	y	n	n
NGC 2320	2.79	-0.27	n	y	0.5	y	y?	n
NGC 2672	...	...	n	y	...	n	y	n
NGC 2768	2.56	-0.08	n	n	0.8	y	n	n
NGC 2810	2.13	-0.05	n	y	0.5	n	n	n
NGC 3656	...	...	n	n	6.1	y	n	y
NGC 4692	2.28	+0.06	y	n	0.3	n	n	n
NGC 5666	2.10	-0.12	n	n	4.9	y	y	y
NGC 6702	...	...	n	n	0.0	y	n	y
NGC 7052	...	...	n	y	0.2	n	n	n
NGC 7330	...	...	n	y	0.0	y	n	n

¹Extracted from the surface photometry, and from visual inspection of the images.

²Average of the color index $(B - I)$ at logarithmic intervals in radius.

³ $\Delta(B - I)/\Delta(\log(r))$ (mag arcsec⁻² per decade in radius).

⁴“y” means the amplitude of the $\cos(4\theta)$ term is positive.

⁵“y” means the amplitude of the $\cos(4\theta)$ term is negative.

⁶Isophotal shift in degrees per kiloparsec of galactic radius.

⁷“y” means dust signatures are observed in the third order Fourier coefficients.

⁸“y” means spiral features are seen on the images.

⁹“y” means the surface photometry and image appear perturbed.

Table 5.3. Ellipticity and Position Angle for the Galaxies at B , I , and K_s Wavelengths

Galaxy	ϵ_B^1	ϵ_I^2	$\epsilon_{K_s}^3$	$(P.A)_B^1$	$(P.A)_I^2$	$(P.A)_{K_s}^3$
<i>(i) KIG catalog</i>						
KIG0083	0.21 ± 0.04	0.21 ± 0.02	0.21 ± 0.02	57.7 ± 3.1	58.1 ± 6.0	55.7 ± 3.4
KIG0089	0.37 ± 0.02	0.37 ± 0.02	0.37 ± 0.04	32.9 ± 0.6	30.7 ± 0.4	32.8 ± 0.9
KIG0120	0.23 ± 0.06	...	0.18 ± 0.05	-33.8 ± 2.9	...	-39.0 ± 3.1
KIG0303	0.55 ± 0.02	0.53 ± 0.02	0.53 ± 0.14	-74.1 ± 1.1	-75.3 ± 1.2	-71.5 ± 1.0
KIG0358	0.30 ± 0.02	0.30 ± 0.02	0.26 ± 0.3	-21.8 ± 1.2	-23.2 ± 0.9	-19.5 ± 0.9
KIG0393	0.18 ± 0.06	0.18 ± 0.04	0.16 ± 0.04	-1.2 ± 30.3	-5.1 ± 27.4	24.4 ± 23.3
KIG0396	0.09 ± 0.03	0.10 ± 0.03	...	-35.7 ± 6.3	-37.4 ± 6.3	...
KIG0503	0.15 ± 0.05	0.16 ± 0.05	0.13 ± 0.04	-41.3 ± 14.0	-53.2 ± 15.1	-61.8 ± 13.4
KIG0732	0.12 ± 0.03	0.11 ± 0.03	0.10 ± 0.03	63.5 ± 4.6	63.9 ± 6.9	$71. \pm 4.9$
KIG0768	0.09 ± 0.05	0.13 ± 0.03	0.12 ± 0.03	-87.0 ± 2.0	-88.2 ± 1.2	-86.0 ± 2.1
KIG0841	0.42 ± 0.02	0.38 ± 0.03	0.36 ± 0.03	-23.0 ± 3.3	-22.4 ± 3.2	-19.0 ± 2.0
KIG1015	0.16 ± 0.05	0.10 ± 0.02	0.07 ± 0.03	-50.1 ± 19.3	-36.5 ± 4.7	$-33.8 \pm 21.$
KIG1042	0.12 ± 0.03	0.10 ± 0.03	...	9.0 ± 10.0	1.0 ± 6.2	...
KIG1045	0.42 ± 0.06	0.42 ± 0.06	0.42 ± 0.06	-41.3 ± 2.3	-43.4 ± 1.0	-43.0 ± 1.2

Table 5.3—Continued

Galaxy	ϵ_B ¹	ϵ_I ²	ϵ_{K_s} ³	$(P.A)_B$ ¹	$(P.A)_I$ ²	$(P.A)_{K_s}$ ³
<i>(ii) Fassano & Bonoli Sample</i>						
UGC5705	0.30 ± 0.03	0.32 ± 0.02	0.29 ± 0.02	74.1 ± 4.0	72.0 ± 5.4	85.6 ± 9.5
UGC6159	0.40 ± 0.10	0.40 ± 0.08	0.34 ± 0.09	-65.8 ± 0.5	-66.8 ± 0.6	-66.2 ± 1.6
UGC6504	0.17 ± 0.03	0.17 ± 0.02	0.17 ± 0.01	-84.4 ± 1.6	-84.4 ± 1.7	-86.7 ± 2.3
UGC6810	0.07 ± 0.02	0.08 ± 0.02	0.07 ± 0.02	-46.1 ± 4.6	-43.5 ± 3.3	-50.3 ± 4.3
UGC7115	0.09 ± 0.03	...	0.06 ± 0.02	-0.3 ± 5.6	...	5.6 ± 2.7
UGC7681	0.09 ± 0.03	...	-20.4 ± 3.6	...		
UGC7767	0.07 ± 0.07	0.07 ± 0.08	...	-81.5 ± 15.9	-81.3 ± 12.3	...
UGC9070	0.20 ± 0.03	0.21 ± 0.02	0.18 ± 0.05	-50.8 ± 1.4	-52.8 ± 1.3	-56.5 ± 3.9
UGC9278	0.26 ± 0.05	0.26 ± 0.05	0.23 ± 0.06	-6.5 ± 1.8	-8.8 ± 1.6	-6.4 ± 2.8
UGC10352	0.09 ± 0.02	0.09 ± 0.02	0.09 ± 0.02	74.7 ± 7.7	76.4 ± 3.8	81.1 ± 5.7
<i>(iii) Hickson Compact Groups Sample</i>						
HCG10b	0.18 ± 0.03	0.18 ± 0.03	...	33.6 ± 11.1	35.5 ± 11.6	...
HCG34a	0.06 ± 0.01	...	0.09 ± 0.01	77.3 ± 8.5	...	83.4 ± 4.7
HCG37a	0.36 ± 0.06	0.37 ± 0.06	0.34 ± 0.05	-14.3 ± 1.0	-15.4 ± 1.1	-14.7 ± 1.0
HCG40a	0.27 ± 0.04	...	0.24 ± 0.05	5.2 ± 2.3	...	8.3 ± 0.7
HCG40b	0.25 ± 0.08	...	0.20 ± 0.05	41.4 ± 8.7	...	42.8 ± 4.3
HCG61a	0.45 ± 0.05	...	0.42 ± 0.05	-26.7 ± 10.3	...	-28.6 ± 7.6
HCG68a	0.46 ± 0.11	0.49 ± 0.10	0.49 ± 0.12	-37.2 ± 2.0	-37.1 ± 1.0	-35.4 ± 1.2
HCG68b	0.20 ± 0.07	0.18 ± 0.04	0.16 ± 0.03	86.1 ± 3.2	87.0 ± 3.6	91.6 ± 2.5
HCG68d	0.27 ± 0.05	0.27 ± 0.04	0.23 ± 0.05	6.1 ± 8.6	3.2 ± 8.2	5.1 ± 1.3
HCG82a	0.32 ± 0.02	...	0.31 ± 0.03	35.2 ± 3.3	...	35.2 ± 1.6
HCG93a	0.07 ± 0.03	0.06 ± 0.03	0.06 ± 0.06	-30.5 ± 12.6	-24.6 ± 11.7	-21.4 ± 10.2

Table 5.3—Continued

Galaxy	ϵ_B^1	ϵ_I^2	$\epsilon_{K_s}^3$	$(P.A)_B^1$	$(P.A)_I^2$	$(P.A)_{K_s}^3$
<i>(iv) Galaxies Known to Contain an ISM</i>						
NGC0759	...	...	0.07 ± 0.02	...	21.3 ± 5.1	...
NGC0807	0.31 ± 0.07	0.30 ± 0.03	0.28 ± 0.05	-37.8 ± 1.7	-40.0 ± 1.6	-41.1 ± 4.8
NGC2128	0.26 ± 0.05	...	0.29 ± 0.03	64.6 ± 3.0	...	62.9 ± 0.8
NGC2320	0.31 ± 0.06	0.35 ± 0.04	0.33 ± 0.05	-37.0 ± 2.7	-38.2 ± 1.8	-39.1 ± 1.3
NGC2768	0.40 ± 0.10	0.39 ± 0.10	0.38 ± 0.13	-84.5 ± 1.5	-86.7 ± 0.7	-83.3 ± 2.2
NGC2810	0.17 ± 0.02	0.17 ± 0.02	0.17 ± 0.02	-41.4 ± 1.1	-40.4 ± 2.3	-47.3 ± 1.4
NGC4692	0.18 ± 0.02	0.17 ± 0.02	0.19 ± 0.03	89.2 ± 1.5	87.2 ± 2.0	92.4 ± 5.02
NGC5666	0.15 ± 0.04	0.16 ± 0.05	0.14 ± 0.02	-26.9 ± 4.4	-26.6 ± 7.3	-27.3 ± 4.2
NGC7052	0.48 ± 0.13	...	...	63.6 ± 1.1	...	...
NGC7330	0.18 ± 0.06	...	0.20 ± 0.07	40.0 ± 4.8	...	40.9 ± 2.8

¹Median averages and standard deviations calculated at logarithmic intervals in radius of the ellipticity profile over the useful range of radius between the minimum and maximum cutoffs. The subscript denotes the filter that was used to obtain the data

²Same information as in the previous footnote, but for the Position Angle profiles.

Table 5.4. M_B and $(B - I)$ For all the Samples

Sample	M_B^1	$(B - I)^2$
KIG	-20.03 ± 0.39	2.12 ± 0.08
F&B	-19.51 ± 0.63	2.18 ± 0.11
HCG	-21.57 ± 0.99	1.99 ± 0.15
ISM	-21.07 ± 0.51	2.39 ± 0.12
Goudfrooij ³	-21.15 ± 0.13	2.05 ± 0.04
Caon et al. ⁴	-19.04 ± 1.48	...

¹Mean and σ of the blue absolute magnitude for each sample.

²Mean and σ of the Color Index $(B - I)$ for each sample.

³For comparison purposes, the values from the sample of elliptical galaxies with $B_T < 12$ of Goudfrooij (1994).

⁴For comparison purposes, the absolute magnitude value of the sample of Caon et al. (1994).

Table 5.5. Fourier Coefficients of the B Band Data

Galaxy	$S3_B^1$	$C3_B^2$	$S4_B^3$	$C4_B^4$	$r(C4_B)^5$
<i>(i) KIG catalog</i>					
KIG 0083	1.81 ± 0.16	1.34 ± 0.15	2.16 ± 0.30	1.75 ± 0.16	8
KIG 0089	0.69 ± 0.07	0.23 ± 0.17	-0.55 ± 0.10	2.44 ± 0.10	20
KIG 0120	-2.40 ± 0.21	1.67 ± 0.21	2.45 ± 0.27	-2.59 ± 0.27	22
KIG 0303	-1.20 ± 0.17	-0.49 ± 0.13	-1.57 ± 0.16	4.55 ± 0.25	20
KIG 0396	-0.67 ± 0.10	0.74 ± 0.10	-0.62 ± 0.09	-0.95 ± 0.09	6
KIG 0503	-2.16 ± 0.13	3.19 ± 0.14	1.01 ± 0.08	2.28 ± 0.09	6
KIG 0732	-1.20 ± 0.08	0.76 ± 0.09	-1.02 ± 0.07	-1.11 ± 0.08	10
KIG 0768	-4.62 ± 0.37	-2.09 ± 0.17	4.62 ± 0.32	-0.92 ± 0.21	11
KIG 0824	1.57 ± 0.20	1.00 ± 0.20	-0.99 ± 0.17	1.38 ± 0.14	9
KIG 0841	3.82 ± 0.45	2.86 ± 0.46	-1.78 ± 0.41	4.42 ± 0.41	10
KIG 1015	-2.52 ± 0.21	-3.99 ± 0.31	-3.08 ± 0.23	2.73 ± 0.24	10
KIG 1042	-3.25 ± 0.22	1.22 ± 0.12	0.00 ± 0.00	2.31 ± 0.12	27
KIG 1045	1.29 ± 0.11	1.28 ± 0.19	2.15 ± 0.08	-2.83 ± 0.10	32

Table 5.5—Continued

Galaxy	$S3_B^1$	$C3_B^2$	$S4_B^3$	$C4_B^4$	$r(C4_B)^5$
<i>(ii) Fassano & Bonoli Sample</i>					
UGC 5705	2.34 ± 0.12	1.28 ± 0.35	4.36 ± 0.21	2.90 ± 0.18	5
UGC 6159	0.38 ± 0.10	0.66 ± 0.22	-0.72 ± 0.08	-1.04 ± 0.11	27
UGC 6504	0.56 ± 0.12	0.68 ± 0.15	-0.40 ± 0.06	0.59 ± 0.05	...
UGC 7767	-1.29 ± 0.09	0.66 ± 0.08	-0.65 ± 0.07	2.08 ± 0.10	4
UGC 9070	0.33 ± 0.19	0.26 ± 0.12	-0.55 ± 0.12	-0.68 ± 0.10	14
UGC 9278	0.55 ± 0.11	-0.58 ± 0.10	0.27 ± 0.05	0.80 ± 0.05	4
UGC 10352	1.64 ± 0.09	0.42 ± 0.09	0.41 ± 0.08	0.60 ± 0.09	9
UGC 10599	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	2.23 ± 0.26	...
<i>(iii) Hickson Compact Groups Sample</i>					
HGC 37a	-1.79 ± 0.11	1.12 ± 0.09	1.29 ± 0.07	-1.86 ± 0.07	10
HGC 40a	0.73 ± 0.11	0.84 ± 0.11	-1.62 ± 0.15	1.71 ± 0.07	7
HGC 40b	2.49 ± 0.27	1.52 ± 0.10	-1.65 ± 0.24	-2.23 ± 0.25	14
HGC 61a	1.75 ± 0.10	-0.57 ± 0.07	0.62 ± 0.05	1.67 ± 0.07	22
HGC 68a	1.24 ± 0.12	-0.64 ± 0.10	0.50 ± 0.07	3.14 ± 0.14	24
HGC 68b	2.26 ± 0.31	-7.88 ± 0.43	-1.72 ± 0.14	-4.73 ± 0.28	8
HGC 68d	-1.26 ± 0.37	2.64 ± 0.54	5.54 ± 0.44	1.35 ± 0.49	24
HGC 82a	0.93 ± 0.15	1.77 ± 0.18	1.38 ± 0.12	-1.62 ± 0.11	13
HGC 93a	0.77 ± 0.13	1.57 ± 0.11	1.02 ± 0.07	-1.68 ± 0.12	43*

Table 5.5—Continued

Galaxy	$S3_B^1$	$C3_B^2$	$S4_B^3$	$C4_B^4$	$r(C4_B)^5$
<i>(iv) Galaxies Known to Contain an ISM</i>					
NGC 759	0.53 ± 0.14	-1.01 ± 0.09	-0.76 ± 0.08	-0.41 ± 0.07	9
NGC 807	5.16 ± 0.83	1.01 ± 0.15	1.82 ± 0.19	1.41 ± 0.16	12
NGC 2128	-0.63 ± 0.17	0.63 ± 0.10	0.63 ± 0.10	2.14 ± 0.13	20
NGC 2320	-8.17 ± 0.46	3.01 ± 2.41	1.74 ± 0.18	-3.09 ± 0.19	11
NGC 2768	1.45 ± 0.11	-3.50 ± 0.18	-2.89 ± 0.19	-3.12 ± 0.07	39
NGC 2810	0.57 ± 0.11	-0.35 ± 0.10	0.50 ± 0.08	-0.65 ± 0.10	20
NGC 4692	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	1.01 ± 0.12	24
NGC 5666	-3.53 ± 0.26	4.68 ± 0.26	3.32 ± 0.24	-1.66 ± 0.14	12
NGC 7052	2.33 ± 0.25	1.22 ± 0.20	1.94 ± 0.22	-3.15 ± 0.30	70
NGC 7330	1.28 ± 0.15	1.31 ± 0.20	1.72 ± 0.19	1.02 ± 0.19	22

¹Average and standard deviation of the three largest (positive or negative) consecutive values in the $S3$ profile multiplied by 100. This is usually called the “characteristic” value by several investigators (see for instance Goudfrooij 1994)

²Same as in footnote 1, but for the $C3$ profile.

³Same as in footnote 1, but for the $S4$ profile.

⁴Same as in footnote 1, but for the $C4$ profile.

⁵radius at which $C4$ was calculated.

Table 5.6. Fourier Coefficients of the I Band Data

Galaxy	$S3_I^1$	$C3_I^2$	$S4_I^3$	$C4_I^4$	$r(C4_I)^5$
<i>(i) KIG catalog</i>					
KIG 0083	1.05 ± 0.14	0.70 ± 0.13	1.60 ± 0.24	1.52 ± 0.16	8
KIG 0089	0.52 ± 0.08	0.58 ± 0.10	-0.46 ± 0.10	2.73 ± 0.11	18
KIG 0303	-0.94 ± 0.15	0.58 ± 0.16	-2.25 ± 0.16	4.12 ± 0.20	17
KIG 0358	0.00 ± 0.00	-0.68 ± 0.12	1.12 ± 0.10	1.35 ± 0.04	9
KIG 0396	-0.66 ± 0.15	1.14 ± 0.14	0.71 ± 0.14	-0.85 ± 0.14	21
KIG 0503	-2.03 ± 0.22	2.08 ± 0.24	0.74 ± 0.08	2.76 ± 0.13	6
KIG 0732	-0.43 ± 0.12	0.37 ± 0.15	-1.49 ± 0.23	-0.82 ± 0.10	12
KIG 0768	-3.50 ± 0.74	3.54 ± 0.57	2.67 ± 0.76	0.93 ± 0.51	11
KIG 0824	1.22 ± 0.16	0.58 ± 0.16	-1.67 ± 0.16	0.42 ± 0.14	10
KIG 0841	2.23 ± 0.16	2.35 ± 0.14	1.18 ± 0.16	1.85 ± 0.13	10
KIG 1015	2.08 ± 0.16	-3.41 ± 0.22	-1.36 ± 0.14	-1.12 ± 0.11	5
KIG 1042	-2.47 ± 0.34	1.04 ± 0.23	1.16 ± 0.17	2.28 ± 0.27	27
KIG 1045	0.70 ± 0.12	0.72 ± 0.13	1.51 ± 0.10	-2.80 ± 0.06	15
<i>(ii) Fassano & Bonoli Sample</i>					
UGC 5705	1.06 ± 0.10	2.43 ± 0.40	3.01 ± 0.23	3.68 ± 0.32	5
UGC 6159	0.18 ± 0.10	0.54 ± 0.22	-0.76 ± 0.11	1.35 ± 0.08	27
UGC 6504	-0.31 ± 0.07	-0.33 ± 0.09	-0.34 ± 0.06	0.70 ± 0.71	12
UGC 7767	-1.26 ± 0.09	0.72 ± 0.66	-0.59 ± 0.19	-0.65 ± 0.07	4
UGC 9070	0.52 ± 0.19	-0.84 ± 0.13	-0.89 ± 0.20	-0.94 ± 0.18	14
UGC 9278	0.80 ± 0.15	-1.22 ± 0.14	0.70 ± 0.13	1.00 ± 0.06	4
UGC 10352	1.13 ± 0.12	0.73 ± 0.18	-0.47 ± 0.19	1.13 ± 0.20	9

Table 5.6—Continued

Galaxy	$S3_I$ ¹	$C3_I$ ²	$S4_I$ ³	$C4_I$ ⁴	$r(C4_I)$ ⁵
<i>(iii) Hickson Compact Groups Sample</i>					
HGC 37a	-1.31 ± 0.13	0.77 ± 0.11	1.08 ± 0.09	-1.57 ± 0.07	9
HGC 68a	1.04 ± 0.09	-0.27 ± 0.10	0.82 ± 0.08	3.29 ± 0.13	24
HGC 68b	1.41 ± 0.14	-3.64 ± 0.14	-0.45 ± 0.08	-2.49 ± 0.12	8
HGC 68d	-2.52 ± 0.25	1.82 ± 0.24	5.07 ± 0.23	2.77 ± 0.19	27
HGC 93a	-0.60 ± 0.11	1.26 ± 0.17	0.66 ± 0.09	-1.18 ± 0.17	43
<i>(iv) Galaxies Known to Contain an ISM</i>					
NGC 807	2.72 ± 0.26	-1.20 ± 0.19	0.83 ± 0.09	0.81 ± 0.09	10
NGC 2320	-2.37 ± 0.12	-0.49 ± 0.16	0.00 ± 0.00	-0.63 ± 0.09	11
NGC 2768	0.53 ± 0.12	-0.99 ± 0.09	-1.39 ± 0.09	-1.60 ± 0.06	39
NGC 2810	0.90 ± 0.15	-0.57 ± 0.08	0.69 ± 0.08	-0.99 ± 0.11	20
NGC 4692	0.75 ± 0.08	0.00 ± 0.00	0.00 ± 0.00	1.53 ± 0.11	22
NGC 5666	-0.71 ± 0.13	3.23 ± 0.16	5.59 ± 0.62	-1.22 ± 0.13	13

¹Average and standard deviation of the three largest (positive or negative) consecutive values in the $S3$ profile multiplied by 100. This is usually called the “characteristic” value by several investigators (see for instance Goudfrooij 1994)

²Same as in footnote 1, but for the $C3$ profile.

³Same as in footnote 1, but for the $S4$ profile.

⁴Same as in footnote 1, but for the $C4$ profile.

⁵radius at which $C4$ was calculated.

Table 5.7. Comparison of Properties Among the Samples ¹

Sample	n^2	Disky	Boxy	Dusty	Spiral	Pert.
KIG	4.2 ± 2.0	53	19	62	43	43
F&B	6.8 ± 3.6	40	10	30	30	10
HCG	4.7 ± 3.5	45	45	36	09	09
ISM	3.7 ± 1.7	23	38	66	20	25

¹the entries in columns 3-7 are percentages for each sample of the properties specified by the header. These results were obtained using the information on Table 5.2

²average and standard deviation of the structure parameter n for each sample

Figure 5.1 This figure compares the Sersic parameter n_B with n_I and r_B with r_I . The lines shown are the best fits to the data

Figure 5.2 This figure is a plot of the Sersic parameter n as a function of the apparent magnitude B_T . Note that the correlation coefficient of the best fit is only 0.06. Therefore, these variables appear to be un-correlated

Figure 5.3 Distribution of galaxies as a function of the Sersic parameter n for different environments. KIG refers to the isolated galaxies in the Karachentseva sample. The top right panel includes the four samples studied in this work. The bottom panels are results from studies of cluster galaxies by Caon et al. (1993) and by Graham et al. (1996).

Figure 5.4 Distribution of galaxies as a function of the logarithm of the Sersic parameter r_e (in kpc) for different environments. KIG refers to the isolated galaxies in the Karachentseva sample. The top right panel includes the four samples studied in this work. The bottom panels are results from studies of cluster galaxies by Caon et al. (1993) and by Graham et al. (1996).

Figure 5.5 This is a plot of the Sersic index $\log(n)$ for the B data as a function of the logarithmic effective radius. Except perhaps for the KIG data, this figure shows a clear correlation between the 2 quantities for all the samples.

Figure 5.6 Plot of $\log(n_I)$ as a function of $\log(r_I)$ including the 4 samples: KIG, FB, HCG and the ISM selected sample. For comparison, the results of Caon et al. (1993) and Graham et al. (1996) are also plotted. A clear correlation is seen between the two quantities. The results from this work and those of Caon et al. show a very good agreement both in slope and scatter. The scatter in the results of Graham et al. is much higher, but shows the same general trend.

Figure 5.7 The top panels present a comparison of $S3_I$ vs. $S3_B$ (left) with $S3_{Ks}$ versus $S3_B$ (right). The bottom panels present a similar comparison for C3. The lines shown are the best fits. The slopes of the left panels ($dS3_I/dS3_B = 0.52$ and $dC3_I/dC3_B = 0.54$) differ by less than 5%. Most galaxies on the right panels were detected by IPAS. Notice that $S3_{Ks} \sim C3_{Ks} \sim 0$.

Figure 5.8 The panels on top present a comparison of $S4_I$ versus $S4_B$ (left) with $S4_{Ks}$ versus $S4_B$ (right). The bottom panels present a similar comparison for the C4 coefficients. The lines shown are the best fits to the data

CHAPTER 6

THE INTERSTELLAR MEDIUM OF EARLY-TYPE GALAXIES

6.1. Introduction

The subject of the ISM content of galaxies is a very important one. The existence and properties of this medium in a galaxy are connected to several important questions in extragalactic research. Its absence implies no star formation. But the presence of even relatively small amounts of cold ISM in a galaxy, almost certainly implies that new stars are capable of forming. It has been proposed that even if just a hot ISM exists in a galaxy, it may still be possible to form stars when the gas finally cools down. But that situation is only beginning to be understood and will not be treated in this discussion.

The characteristics of the ISM are also strongly correlated with the morphology of galaxies. Not too long ago, early-types were thought to be devoid of an ISM, whereas late-types were known to contain substantial ISMs. Nowadays, that picture has changed considerably for the early-type galaxies. But in spite of the new interpretations, the differences between the ISM in early-type and late-type galaxies are great.

Indeed, the history of formation and evolution of galaxies, regardless of

whether these events happen through internal processes, or through external ones, as in cases of interactions and mergers, must be tied to the ISM history of these objects. With the hope of gaining new insight about the properties of the cold ISM, and their relation to the morphology and environment in early-type galaxies, three different studies have been attempted in this work. These studies are: (1) Observations of the CO(1-0) emission line in a sample of isolated elliptical galaxies. (2) Observations of the sub-millimeter continuum emission by dust for a small sample of isolated elliptical galaxies. (3) A study of the morphological properties of a sample of early-type galaxies known to possess an ISM. The morphology of the galaxies is studied through the analysis of the optical and infrared data presented earlier in this thesis.

6.2. Historical Background

Not too long ago, except for a few well known cases of dusty early-types, it was generally agreed that early-types do not possess significant amounts of ISM. That view has suffered important revisions since the 1980's, when observational results at several spectral regions began to become available. A decisive role in this change of perception was due to the development and implementation of astronomical satellites that were finally able to observe the universe unobstructed by the veil of the earth's atmosphere. Indeed, two of the most important discoveries were accomplished at wavelengths where the atmosphere is so opaque, that these would have been impossible to do from observatories on the ground. One of these major breakthroughs occurred at the x-ray wavelengths, with the discovery, mainly due to the Einstein satellite, of vast amounts of hot gas in some elliptical galaxies (Fabbiano et al. 1992). The other important finding occurred at the opposite side of the spectrum, in the far infrared region, where the Infrared Astronomy satellite

(IRAS) proved the existence of dust in a high percentage of early-type galaxies (Jura et al. 1987).

In addition to the space observatories, very important contributions have been made by telescopes on the ground, observing at infrared, optical, and radio wavelengths. The significance of these contributions can be seen by the wealth of information that has been obtained about the cold phase component of the ISM using millimeter and sub-millimeter telescopes from the ground. In spite of these successes, however, we are still far from having a complete picture of the ISM in early-type galaxies. A better understanding of this medium in early-type galaxies would be very valuable, because it could give us more clues about the origin and evolution of these objects.

6.2.1. The ISM in Isolated Early-Type Galaxies

Haynes and Giovanelli (1980, 1983, 1984) did the first systematic studies of the ISM in isolated galaxies. They searched for HI in a sub-set of galaxies from the "Catalog of Isolated Galaxies" (Karachentseva 1973) that are also included in the UGC catalog (Nilson 1973). In spite of their study of the degree of isolation of their sample (Haynes and Giovanelli 1983), where they concluded that most of their galaxies lie in the outskirts of clusters, their galaxies really are almost devoid of interactions with other galaxies and are considerably less affected by the intra cluster ram pressure than most cluster galaxies. Therefore, their sample can be considered to be a good approximation to truly isolated galaxies.

In their preliminary study of isolated early-type galaxies, Haynes and Giovanelli (1980) found a significant amount of H I in the five galaxies they studied. From that work it was concluded that if the galaxies were truly early-types (as

opposed to misclassified spirals), the presence of HI would impose severe constraints on the efficiency of their internal ISM removal mechanism. In other words, their results were consistent with the interpretation that in the absence of ram pressure from the cluster and of an efficient internal mechanism for removing the ISM from early-type galaxies, the ISM of these galaxies could be rich, due to the continuous mass loss from stars.

The preliminary results for isolated early-types from Haynes and Giovanelli (1980) were superseded, however, by the results of the full sample (Haynes and Giovanelli 1984) in which 10 out of 24 isolated early-type galaxies (with a numerical coding $T=0$ for elliptical and $T=1$ for S0) had HI detections. In the light of the results of the full sample, the initial conclusions reached by Haynes and Giovanelli became somewhat weaker, leaving the following question without a definite answer: Do isolated galaxies contain more HI than those in clusters?

More recently, Huchtmeier et al. (1995) have also found high detection rates for isolated early-type galaxies. Furthermore, similar results have been found for the CO (Wiklind et al. 1995). In fact, Wiklind et al. have claimed that "Field ellipticals are more likely to contain an observable molecular gas component than those residing in groups or clusters".

The investigations mentioned above seem to suggest that in the absence of ram pressure from intra-cluster gas, the ISM in isolated galaxies appears to be richer than those in galaxies that inhabit the more common cluster environments. It is worth investigating the validity of this hypothesis by studying the relation between the ISM and the environment of early-type galaxies. To do this, one must recognize from the outset, that the so far unavoidable problem of morphological misclassification, is an extremely important variable in the interpretation of the

results. Likewise, it is important to recognize, that contrary to the old view, in which the role of mergers and gravitational interactions was not fully appreciated, the source of ISM in isolated early-types might not be due to internal processes in a galaxy, but rather, due to external sources. In fact, the presence of a cold ISM in isolated early-types is probably due to material acquired from late-type galaxy companions during a merger process in the recent past (Goudfrooij 1994).

The important aspect of studying a sample of isolated galaxies is that we can, in principle, remove from the analysis effects from the environment such as the ram pressure, as well as obvious gravitational interactions with other galaxies (note that mergers are still considered). One can then concentrate on studying, whatever the case may be, either the intrinsic properties of a galaxy, or perhaps more likely, the later stages of mergers or post-merger phase of evolution of an isolated early-type galaxy.

6.3. The Molecular Component of Early-Type Galaxies

Although the IRAS satellite established the presence of dust in a high percentage of early-types, the presence of cold gas in either atomic (H I) or molecular (H_2 , CO) form has been more challenging to prove in a statistical fashion. Roberts et al. (1991) provide a useful catalog of the ISM measurements in early-type galaxies for all the galaxies in the Revised-Shapley-Ames Catalog of Bright Galaxies (RSA) prior to 1991. A more recent review has been presented by Henkel and Wiklind (1997). Efforts to study CO in early-type galaxies have been reported by Wiklind and Henkel (1989), Lees et al. (1991), Wiklind and Rydbeck (1986), Roberts et al. (1991), Bregman et al. (1992), Wang and Kenney (1992), Sofue and Wakamatsu (1993), Sage and Galleta (1993), Wiklind et al. (1995), Knapp and Rupen (1996),

etc. But most of these studies have been strongly biased to highly luminous IRAS sources, galaxies with dust lanes, or galaxies that are known mergers. The selection of galaxies in most cases were made to enhance the chances for CO detection, and have indeed provided valuable information, because these searches have succeeded in proving that CO is present in some early-type galaxies. Unfortunately, such studies do not provide enough information to characterize the whole population of early-type galaxies, nor do they tell us about the dependence of the ISM with respect to the environment. Reasonably unbiased samples are needed to solve the first issue, whereas studies with samples of galaxies in different environments need to be done to address the second.

6.3.1. CO(1-0) Observations with the NRAO 12-Meter Telescope

A project was carried out to search for CO(1-0) emission in isolated early-type galaxies. These observations were done using the NRAO 12-Meter millimeter telescope at Kitt Peak in Feb 1995. The CO(1-0) line is the lowest rotational transition of the CO molecule, and it plays a very important role in astronomy, because it makes possible to get information on the total molecular gas component of galaxies (within the uncertainties associated with a CO/H₂ conversion factor). The goal was to search for the CO(1-0) rotational transition in six isolated early-type galaxies, that were among the 10 isolated early-types detected in H I by Haynes and Giovanelli (1984), and that were also detected by IRAS at 100 μ m. The main purpose of this investigation was to get information on the molecular gas content in isolated early-type galaxies. A combination of these results with those of the neutral atomic hydrogen already known (Haynes and Giovanelli 1984), would then give us the total gas content.

The instrument used for the observations at the NRAO 12-m telescope on

Kitt Peak was a 90-116 GHz receiver, along with two different spectrometers that were used simultaneously. The Hybrid spectrometer has 768 channels and a total bandwidth of 600 MHz., giving a 2.03 km/s/channel resolution. The filter-bank spectrometer has 256 channels, a total bandwidth of 256MHz, and a resolution of 2.6 km/s/channel resolution. The observations were made on Feb 21-22 1995 under cloudy conditions. The system temperature stayed between 320 K and 420 K during most of the run. To search for the CO(1-0) emission, the receiver was tuned to the redshift of the galaxies obtained by Haynes and Giovanelli (1984) during their HI search. The observations were carried out by chopping the secondary with a beam throw of either 2 or 3 arc minutes, depending on the size of the angular diameter of the galaxy that was being investigated. Pointing and focusing were done several times during the run. All the spectra taken turned out to have very stable baselines, without any significant slope.

6.3.2. Results of the CO(1-0) Observations

Assuming a bandwidth for the CO(1-0) line to be the same as the HI bandwidth (Haynes and Giovanelli 1984), the I_{CO} was obtained by integrating the emission over this velocity range. To obtain the H_2 mass, the N_{H_2}/I_{CO} factor obtained by Scoville (1989) was used. The summary of the results are presented in Table 6.1. The galaxy KIG 1015 was detected at $6 \times \sigma$. Therefore, this is an almost certain detection. The galaxy KIG 83 was tentatively detected. For two galaxies (KIG 128 and KIG 483) the signal to noise ratio is 2.8. These can be considered as near detections that need confirmation. Finally, the galaxies KIG 89, and KIG 760 were not detected. Among the six galaxies studied, KIG 83 (also known as UGC 1503) is the only one that has been previously studied. From observations made at the IRAM 30-meter telescope, Wiklind et al. (1995) detected CO(1-0) for this galaxy.

They found that KIG 83 contains 1.34×10^9 solar masses of H_2 gas. This number is almost a factor of two higher than the value reported here. This might be due to the fact that in this work only a weak detection was found. For comparison, the mass of HI reported by Haynes and Giovanelli (1984) is also presented on Table 6.1.

6.4. The Dust Component in Early-Type Galaxies

Prior to the 1980's, very little was known about the ISM in early-type galaxies. At that time, the observations suggested that these galaxies possess very small amounts of ISM. It was also clear, however, at least to some astronomers, that ellipticals could be hiding dust as well as other components of the ISM. Faber and Gallagher (1976) argued that this could be the case. It was already well known that large numbers of stars in early-type galaxies are red giants, and that such stars shed appreciable amounts of mass into the ISM. Faber and Gallagher (1976) estimated that the mass loss was given by $0.015 \times 10^{-9} L_B / L_\odot$ in solar masses per year. Knapp et al (1992) found several years later basically the same result. If those stars have been shedding mass at this rate for a significant fraction of the Hubble time, it was thought that such matter should be detectable, unless it has been removed by an efficient mechanism.

The knowledge of the cold dust component of the ISM in early-type galaxies has been growing steadily since the launch of IRAS. Knapp et al. (1989) found that 45% of early-type galaxies with $B_T < 14$ were detected at both $60\mu\text{m}$ and $100\mu\text{m}$ by IRAS, thus showing the widespread presence of cold dust in these galaxies. After IRAS, there have been important developments due to ground-based telescopes and detectors working at the millimeter and sub-millimeter region of the spectrum,

that have permitted to obtain quantitative information about the cold dust content of galaxies. The first detection of thermal dust emission at millimeter wavelengths from an elliptical galaxy was done by Fich and Hodge (1991), where they reported 1.1 mm observations of NGC 205. From that study, they were able to derive the temperature as well as the amount of dust present in that galaxy. They also (Fich and Hodge 1993) expanded the number of early-type galaxies with dust detection, by searching for dust among 22 galaxies detected by IRAS. From that study they were able to obtain detections of $3 \times \sigma$ or better for six of the galaxies. Another important contribution was done by Wiklind and Henkel (1995), who detected 5 galaxies at more than $3 \times \sigma$. But, over all, quantitative studies of dust in early-type galaxies are scarce, due to the degree of difficulty involved in detecting dust in these galaxies with current technology.

6.4.1. Observations of Dust in Early-Type Galaxies with the HHT

With the goal of improving our understanding about the dust content of isolated early-type galaxies, sub millimeter dust continuum emission observations were carried out at the 10-meter Heinrich Hertz Submillimeter Telescope (SMT). The observations were done with the CONOFF routine, which places the source alternatively in the plus or minus azimuth beams. The chop rate was set to a relatively high value of 5 Hz. Usually, 50 or 100 on-off pairs of sub scans with an integration time of 10 seconds were taken. The galaxies were observed at either $\lambda = 1.2$ mm or at $\lambda = 0.8$ mm. Whenever the water vapor atmospheric opacity was appropriately low, preference was given to the higher frequency, 0.8 mm observations.

6.4.2. Results of the Search for Dust at the HHT

The data reductions were done using the standard reduction package *ONOFF*, that basically provides the mean and RMS for each subscan. Then a simple fortran program was used to calculate the mean and RMS values for the combination of all the subsamples for each of the objects and wavelengths. The data were calibrated by simply dividing the known flux density of one of the calibrators by the number of units (the mean value corrected for zero opacity). For the 0.8 mm observations, a scale of 53.9 Jy/unit was obtained for Saturn, 60.16 Jy/unit for W30H, and 53.7 for K 350a. To calibrate the 0.8 mm observations the value obtained for Saturn was used. Likewise, the 1.2 mm calibrations were done using the corresponding scale obtained for Saturn.

The main results of the dust search are presented in Table 6.2. As this table shows, no detections were found for any of the galaxies under investigation. It is important to mention, however, that all the calibration sources were detected, and that consistent results from the different calibrators were obtained. This means that the instruments were working properly at the HHT. The only reason for the non-detections is due to the weak dust continuum emission of the galaxies studied. Clearly, a telescope larger than the HHT is needed to detect these sources. This in fact has been achieved by Fich and Hodge (1993) for NGC 404, and by Wiklind and Henkel (1995), to detect NGC 2320 and NGC5666.

Whenever the dust continuum emission is detected or even when small upper limits are found at mm and sub-mm wavelengths, it is possible to find the temperature and dust content of a galaxy. In this work, however the limits are too high to constrain the data. This is illustrated on Figure 6.1, where the emission, which is given by the product of the emissivity of the dust grains multiplied by the

Planck function has been plotted. The emissivity is usually modeled as a power law of the frequency (Fich and Hodge 1991, and Hildebrand 1983). In the same figure, the far infrared data from IRAS and the results from this work for the galaxy NGC 2654 are presented. Figure 6.1 shows that the $60\mu\text{m}$ and the $100\mu\text{m}$ data are useful for constraining the parameters of the model for emission. However, the 0.8 mm and the 1.2 mm values are too high to be useful.

6.5. The Morphological Structures of Early-Type Galaxies known to contain an ISM

There have been several works dedicated to study the ISM in early-type galaxies. The references for many of the successful searches for neutral hydrogen, molecular gas, and dust have been given in previous sections in this chapter. But virtually all of that work has been carried out at millimeter and radio wavelengths, without studying the morphology of these galaxies. The main purpose of the present investigation, is to verify that the galaxies known to contain an interstellar medium, claimed to be early-types are representative of the common population of early-type galaxies. Another objective of this investigation, is to study the “fine” structures that are present in these galaxies. In the context of this particular sample such structures are expected to be due to dust lanes, signatures from mergers, or even spiral arms in cases of clearly misclassified galaxies.

The morphological classification is very important in determining the properties of galaxies. Regarding the study of the relation between the cold ISM content and the morphology of galaxies that will be taken up here, the following facts are important. It has been discussed in this chapter how difficult it is to establish the presence of cold gas and dust in an early-type galaxy with the

current technology and astronomical infrastructure. In contrast, it is relatively easy to obtain high quality optical images with 2-meter telescopes for most of the galaxies at low redshift. There have been several detections of cold ISM in early-type galaxies in recent years. This may have led people to believe that cold ISM has been found in ordinary cluster elliptical galaxies. This work simply put this hypothesis to a test. With this purpose a sample of 19 galaxies claimed to be early-type that are known to have a cold ISM have been studied. Optical and near IR wavelengths images were taken, with the goal of finding underlying structures due to spiral arms, dust structures, merger signatures etc. The list of galaxies selected was given in chapter 2, the observing log and the results of surface photometry are in Chapters 3 and 4 for the optical and IR data respectively. The images are presented in Appendix A, and the comments for the individual objects are in Appendix B. The results extracted for the 19 galaxies with detected ISM studied in this work areas follows.

- (1) Five galaxies present clear spiral structures. These galaxies are: UGC 1503 (same as KIG 83), NGC 807, NGC 3928, NGC 5666 and NGC 6524 (same as KIG 841). These spiral structures can be seen in Appendix A (i.e., these are all misclassified)
- (2) The galaxies NGC 3597 (Taniguchi et al. 1990 and Lutz 1991) and NGC 3656 (Balcells 1997 and Balcells and Stanford 1990) are well known cases of mergers. Wiklind et al. (1997) suggest that NGC 759 is also a late stage of a merger between 2 gas rich disk galaxies. NGC 6166 is the dominant galaxy in the A2199 cluster. It really consists of more than one galaxy. The major galaxy appears to be in the process of cannibalizing the other components (see Appendix A). NGC 2672 (Arp 167) is interacting or merging with NGC 2673. Evidence for tails can be seen in

the image in Appendix A. It is shown by this work that NGC 2783 (same as HCG 37a) has shells (see HCG 37a in appendix A). All together, there are 6 mergers or merger candidates.

(3) 6 galaxies have dust lanes (NGC 2128, NGC 2320, NGC 2534, NGC 2768, NGC 6702 and NGC 7052). The dust components of the first 5 galaxies in this list can be seen in Appendix A. For galaxy NGC 7052 it is difficult to see the dust lane with ground base data. Quillen et al. (2000) have studied NGC 7052 with NICMOS. They have found a dust lane in the core of this galaxy.

(4) Galaxy NGC 855 is a dwarf galaxy that does not have elliptical isophotes in the inner regions of the galaxy.

(5) The only remaining galaxy in the sample is NGC 2810. H I has been detected for this galaxy (Huchtmeier et al. 1995), but it was only detected at $60\mu\text{m}$ by IRAS (it was not detected at $100\mu\text{m}$). Furthermore, no molecular observations have been reported. Therefore, this is in fact the weakest case for ISM detection in the sample.

Although this study includes only a fraction of the galaxies classified as early-type known to contain a cold ISM, it is clear from the images presented here, that the galaxies that have been detected so far do not correspond to the featureless galaxies normally associated with elliptical galaxies. Clearly, a similar study for all the galaxies known to contain an ISM would be very valuable in order to have a better assessment of the presence of a cold ISM in typical early-type galaxies.

The main results of this chapter can be summarized as follows. From the observations at the 12-Meter NRAO telescope, CO(1-0) was detected for KIG 83 and KIG 1015. Galaxies KIG 128 and KIG 483 were nearly detected. The masses

of H_2 found are $2.23 \times 10^9 M_\odot$ for KIG 83 and $1.02 \times 10^9 M_\odot$ for KIG 1015. The mass of KIG 83 (also known as UGC 1503) had previously been measured by Wiklind et al. (1995) using the IRAM 30-Meter telescope. They obtained a mass of H_2 of $1.34 \times 10^9 M_\odot$. The discrepancy in the results is probably due to beam size effect, or to the low $3.1 \times \sigma$ detection of this work. No detections were found from the search for dust with the HHT. Since the calibration sources were detected with consistent results it is deduced that the HHT was operating properly, but the dust signals from the galaxies were too faint to be detected. From the morphological study of the sample of early-types with detected ISM, the main result is, that no galaxy with detected molecular component corresponds to the featureless elliptical galaxies in clusters.

TABLE 6.1
CO(1-0) OBSERVATIONS OF ISOLATED EARLY-TYPE GALAXIES AT THE NRAO 12-M

Galaxy Name ^a	Galaxy Name ^b	V^c km s ⁻¹	ΔV^c km s ⁻¹	RMS mK	S/N	I_{CO} K km s ⁻¹	$M_{H_2}^f$ $10^8 M_\odot$	M_{HI}^g $10^9 M_\odot$
KIG 83	UGC 1503	5085	288	4.60	3.1	0.351	7.20	2.23
KIG 89	NGC 821	1716	—	4.00	—	< 0.296 ^e	< 0.66 ^e	—
KIG 128	NGC 1349	6596	382	2.90	2.8	< 0.370	< 12.8	5.12
KIG 483	NGC 3716	6636	597	2.30	2.8	< 0.247	< 2.72	3.63
KIG 769	UGC 10528	4274	496	3.20	1.7	< 0.171	< 2.46	4.78
KIG 1015	IC 5315	4431	180	3.20	6.0	0.373	13.28	1.02

^aGalaxy name in the Catalog of Isolated Galaxies (Karchentseva 1973).

^bMost common galaxy name.

^cHI data from Haynes and Giovanelli (1984).

^dRoot mean square of the binned data.

^eThis value is uncertain because ΔV is not known.

^fMass of molecular hydrogen, assuming M_{H_2}/M_{CO} as in Scoville et al (1986).

^gMass of atomic hydrogen, calculated from data on Haynes and Giovanelli (1984), assuming $H_0=75$ km s⁻¹

TABLE 6.2
SEARCH FOR DUST IN EARLY-TYPE GALAXIES

Galaxy	100 μm^{a}	60 μm^{a}	25 μm^{a}	12 μm^{a}	800 μm^{b}	1200 μm^{b}
NGC 0404	3.989	2.143	0.204	< 0.108	< 1.150	< 4.580
UGC 1503	1.468	0.426	< 0.118	< 0.098	< 0.989	< 5.530
NGC 0807	1.606	0.351	< 0.129	< 0.141	< 2.350	
NGC 2320	1.237	0.246	< 0.087	< 0.099		< 0.370
NGC 2654	1.536	0.438	< 0.106	< 0.068	< 0.511	< 0.311
NGC 3928	5.065	2.799	0.391	0.208	< 0.557	
NGC 5666	3.545	1.751	< 0.195	< 0.132	< 0.690	< 0.370
NGC 6524	7.332	3.386	0.325	0.234	< 0.340	

^aIRAS flux densities

^b $3 \times \sigma$ flux limits from data obtained at the HHT submillimeter Telescope

Figure 6.1 The observed 0.8mm and 1.2mm flux densities obtained at the HHT are shown with filled stars. The IRAS data points are shown with blank stars. The lines are models of the continuum emission for $T=25\text{K}$ and $\beta = 1.5$ (lower) or $\beta = 2.0$ (top). This figure illustrates that the upper limits for the flux density obtained at the HHT are too large to be useful for constraining the data.

CHAPTER 7

FINAL DISCUSSION

7.1. Introduction

Contrary to ellipticals in clusters that very likely formed at large redshift, isolated ellipticals might form continuously as a function of redshift (Ellis et al. 2000). This thesis explores the possibility that isolated elliptical are forming at the present time. This is done by studying different samples of early-type galaxies with the goal of learning about the properties of galaxies that lie in relatively isolated regions of the universe, outside of clusters, and possibly even in the outskirts of clusters. The conclusions of this work are based on a direct analysis of optical and near IR imaging data specifically obtained for this project, as well as relevant data that has been culled from the literature for some of these objects (IRAS data, for instance).

Four different samples have been studied. The most important for this investigation consists of a sample of 39 galaxies classified as early-types in the KIG catalog (Karachentseva 1973); a sample of relatively isolated galaxies previously studied by Fasano and Bonoli (1989); a sample of HCG galaxies (Hickson 1982); and a sample of galaxies with detected ISM extracted from several sources (Knapp et al. 1989, Fich and Hodge 1993, Huchtmeier 1994, Huchtmeier et al. 1995, Lees

et al. 1991, Wiklind et al. 1995, Wiklind and Henkel 1995, and possibly others).

7.2. The properties of the KIG Sample

From the morphological study of the KIG it has been found that the percentage of isolated elliptical galaxies in the KIG represents no more than 6% of the total population of galaxies in that catalog. This low percentage of ellipticals combined with the high detection rate of mergers in the same sample, is used to estimate the merger lifetime of compact groups. The results confirm that merging processes are indeed happening right now in isolated regions of the universe. The figures in Appendix A present images of several of these cases. Much of our knowledge about merging in compact groups, comes from numerical simulation studies that have been carried out since the 1970's. The pioneering work of Toomre and Toomre (1972), and Toomre (1977) introduced the first suggestions that mergers were major players in the formation and evolution of galaxies. Further theoretical work done by Carnevaly et al. (1981), Barnes (1985); Barnes (1989), White (1990), Diaferio et al. (1994), Weil and Hernquist (1996), Mihos (1995), Governato et al. (1996), Athanassoula et al. (1997) and several others, have shown that indeed compact groups appear to evolve into elliptical galaxies. The short crossing times of most compact groups appear to suggest that they can only last for a fraction of the Hubble time. Thus the present population of isolated compact groups that exists today is probably a transient population that formed in relatively high density regions within loose groups, as proposed by Schweizer (1989), and White (1990). There is however no agreement on how fast the merging of groups occurs. Simulations of Barnes (1989) suggested that compact groups could evolve in ellipticals in a fraction of the Hubble time. Athanassoula et al. (1997) have suggested, however, a wide range of lifetimes for the group, depending on the mass

distribution in the halo and on the initial conditions in the group.

Theoretical models that find merger lifetimes of a few ($\sim 2 - 5$) Gyr. are consistent with our empirical estimation. Slow models that predict lifetimes larger than the Hubble time are ruled out, because they cannot account for the number of mergers observed, and merger features cannot last for a Hubble time. However, very fast evolution models for compact groups (lifetime < 1 Gyr) present a problem too, because they predict a number of isolated ellipticals that is not observed. If a significant number of compact groups actually evolve fast, the over-production of ellipticals could imply that isolated ellipticals probably experience a post-merger evolution, that would change their morphology to spirals. This could happen if they are able to collect enough matter from the IGM, to be able to form a disk and eventually be able to form spiral arms. Although this argument can adequately explain the results obtained for the KIG, it is very speculative at the present time. Nevertheless, Kauffmann (1995) has suggested that isolated ellipticals can go through this process.

7.3. Results from the surface photometry study

Due to the usefulness of the harmonic parameters in determining galaxy properties, this study compares the “characteristic” values of the harmonic amplitudes at different wavelengths. Through this analysis, it is shown that the third order harmonic amplitudes (S3, C3) carry information about the dust content in early-type galaxies. It has also been confirmed that the fourth order cosine coefficient (C4) gives structural information about the galaxies. This information is then used to obtain global parameters for each of the galaxies for which surface photometry is available. The results are presented in Table 5.2 for each of the

galaxies, and in Table 5.7 for each sample. After comparing the results for the 4 samples, the following results emerge.

Aside from the high percentage of galaxies with spiral features and with the high percentage of candidate mergers or perturbed galaxies, the KIG sample has been found to be composed of galaxies that are dusty and disky. Five galaxies in the KIG have positive color gradient, which probably means that they are forming stars near their nuclei. In fact 4 of these galaxies are in the list for candidate mergers, while the remaining galaxy have spiral arms in the central region. Mihos and Hernquist (1994) have suggested that this blue light can be detectable for several Gyr (if the starburst is characterized by solar metallicity). Further studies will be needed to show if these galaxies are related to the field galaxies with blue nuclei that have been found by Ellis et al. (2000) and Menanteau et al. (1999). The KIG sample, indeed appears to be composed of a very unique set of galaxies. Because of the characteristics of the sample, these properties appear to be primarily related to the high degree of isolation of its members. In retrospect these results should have been expected. It is well known that a large percentage of the ultraluminous infrared galaxies are also isolated, dusty and are experiencing or have experienced merging events in their recent past (Kormendy and Sanders 1992). It has also been claimed that the isolated galaxies have the highest detection rates of dust lanes (Ebner et al. 1988), the highest percentage of shells (Malin and Carter 1983).

The most evident results from the surface photometry for the other 3 samples are the following. Except for 2 galaxies (UGC 1503 and UGC 5705) in the Fasano and Bonoli sample that happen to be also in the detected ISM sample (one is also in the KIG), the rest of the galaxies in this sample are found to consist of mostly

well behaved elliptical galaxies. The most notable result for the HCG sample is that it has the largest percentage (45%) of boxy galaxies. One of the galaxies HCG 61a is also in the detected ISM sample. For this galaxy a structure of shells has been found. As expected, the sample with detected ISM contains the highest percentage (66%) of dusty early-types, and a significant percentage (38%) of boxy galaxies. The numbers found in this work are well within the percentages found by Bender et al. (1988), and Rix (1991).

The surface photometry analysis was also used to investigate the surface brightness profile. The B and I profiles were fitted with Sersic functions. This function reduces to the de Vaucouleurs law or to a disk exponential profile for Sersic indices equal to 4 and 1 respectively. Only a handful of galaxies was found to obey the de Vaucouleurs law. On the average, however, most of the galaxies did not deviate too far from $n = 4$. The results for the Sersic parameters obtained at the two wavelengths were compared. The parameters turned out to be very similar. This was in fact surprising, since many of the galaxies studied are dusty. The most important result found from this study, is the correlation that exists between the log of the Sersic index and the log of the effective radius. The results from this correlation agree quite well with the results obtained by Caon (1993) (Figure 5.7). Furthermore, we have shown that this correlation appears to be independent of the environment.

7.4. The ISM in early-type galaxies

Another topic that has been studied in this work is the cold ISM in early-type galaxies. There have been several reports in recent years claiming that a cold ISM component is present in early-type galaxies. By studying 19 early-type galaxies

with detected ISM, this work has attempted to find out whether any of such galaxies correspond to the population of featureless galaxies normally associated with elliptical galaxies. The main result of this study is, that *none* of the early-type galaxies with a detected molecular or dust component (detected at submillimetre wavelengths) corresponds to a featureless elliptical.

Besides the morphological study of the ISM detected galaxies, direct detection of the molecular and dust components were attempted. The search for dust at the HHT telescope was unsuccessful, because none of the galaxies was detected. However, the search for CO reported two detections from a total of 6 objects investigated. The galaxies detected are KIG 1015, and KIG 83. The first is a perturbed galaxy, and the second has a clear spiral structure.

7.5. Plans For Future work

There are a number of investigations that could be carried out to confirm and extend the results of this thesis.

- 1) To study the full Karachentseva sample of isolated galaxies that have been classified as early-type in the KIG as well as in other catalogs. This would permit to have more robust conclusions about the percentage of isolated early-type galaxies, percentage of mergers, etc. If the conclusions of this thesis are valid, such a study could also serve as a method for finding unknown mergers.
- 2) Study the merger candidates as well as other interesting galaxies in more detail. To study the star formation and internal dynamics, image the central regions at higher resolution and obtain deeper images of the outer edges. It would also be very interesting to image the merger candidates as well as some of the isolated galaxies at x-ray wavelengths to see whether these galaxies are surrounded by hot

gas. Mulchaey and Zabludoff (1999) have already detected the remnant gas from the isolated elliptical galaxy NGC 1132. They claim that the hot x-ray gas is the fossil remnant of a poor group of galaxies that merged into NGC 1132.

3) To calibrate the objects studied, to be able to have absolute photometry for them. This could be done by taking fast exposures of the objects.

4) To increase the sample of galaxies with detected ISM, in order to improve the statistical results for that sample. Our finding that none of the ISM detected galaxies can be characterized as a normal elliptical (for the reasons explained at length in chapter 6). is at odds with claims that a significant percentage of ellipticals contain an ISM. By studying a larger sample we could have a better assessment of this issue.

5) High resolution spectroscopy, to obtain velocity dispersions to study the fundamental plane for the galaxies in the KIG. It would also be interesting to study the candidate mergers to see if they are going through a starburst phase.

6) Study the "Entropic Plane" (Lima Neto et al. 1999, Marquez et al. 2000.) for the Sersic parameters. It has been found that to a good approximation (of about $\sim 10\%$) ellipticals in clusters have a unique specific entropy. We should be able to test with our results if the same holds true for the isolated ellipticals in the KIG. Possible tests for the hierarchical formation can also be carried out.

Appendix A: Direct and Residual Images for the Galaxies in the Four Samples

I-band image of KIG 74.

Direct and residual I-band images of KIG 83.

Direct I and residual B-band images of KIG 89.

Direct and residual B-band images of KIG 120.

Direct and residual B-band images of KIG 128.

Direct and residual I-band
images of KIG 179.

B-band image of KIG 248.

Direct and residual B-band
images of KIG 303.

B-band image of KIG 308.

Direct and residual I-band
images of KIG 358.

Direct and residual B-band
images of KIG 393.

Direct I and B residuals of
KIG 396.

Direct Ks image of KIG 437.

Direct I image of KIG 443.

Direct I image of KIG 467.

I-band image of KIG 501.

I-band image of KIG 503.

I-band image of KIG 505.

I-band image of KIG 511.

B-band image of KIG 537 at
different contrasts.

V-band image of KIG 555.

B-band image of KIG 633.

Direct and residual B-band images of KIG 705.

B-band image of KIG 714.

I-band image of KIG 721.

Direct and residual B-band
images of KIG 732.

Direct and residual B-band
images of KIG 768.

B-band image of KIG 769.

B-band image of KIG 798.

I-band image of KIG 824.
of KIG 128.

B-band image of KIG 826.

B-band image of KIG 829.

B-band image of KIG 836.

B-band image of KIG 841.

B and I-band images of
KIG 894.

Direct and residual B-band
images of KIG 1015.

B-band image of KIG 1042.

Direct and residual I images
of KIG 1045.

Direct and residual B-band
images of UGC 5705.

Direct and residual B-band
images of UGC 6159.

Direct and residual B-band
images of UGC 6504.

Direct and residual B-band
images of UGC 6810.

Direct and residual B-band
images of UGC 7115.

Direct and residual B-band
images of UGC 7681.

Direct and residual B-band
images of UGC 7767.

Direct and residual B-band
images of UGC 9070.

Direct and residual B-band
images of UGC 9278.

Direct and residual B images
images of UGC 10352.

Direct and residual B-band
images of HCG 10b.

Direct and residual B-band
images of HCG 34a.

Direct and residual B-band
images of HCG 37a.

B-band direct and Ks residual
images of HCG 40a.

Direct and residual B-band
images of HCG 61a.

B-band and I-band images of
HCG 68a,b.

I-band image of HCG 68d.

B-band image of HCG 82a,b.

Direct I-band image of
HCG 93a.

Direct and residual B-band
images of NGC 759.

Direct and residual B-band
images of NGC 807.

B-band image of NGC 855,
at different contrasts.

I-band image of NGC 2128.

Direct B and residual I-band
images of NGC 2320.

B-band and I-band images of
NGC 2534.

B-band image of NGC 2672.

B-band and I-band images of
NGC 2768.

Direct and residual B-band
images of NGC 2810.

B-band image of NGC 3597 at
different contrasts.

B-band image of NGC 3656.

B-band image of NGC 3928.

Direct and residual B-band images of NGC 5217.

B-band image of NGC 5666 at different contrasts.

B-band direct and residual images of NGC 6702.

B-band direct and residual
images of NGC 7052.

B-band direct and residual
images of NGC 7330.

Appendix B: Comments for Individual Objects

• Comments for Galaxies from the KIG Sample

KIG 74. This compact galaxy appears to be a barred spiral. It is highly asymmetric. Zwicky (1968) describes it as a blue post-eruptive pear-shaped galaxy [CGPG]. It was detected by IRAS.

KIG 83. Classified as E by Karachentseva (1973), as well as in the NED. However, we find clear spiral features, particularly after subtracting a model elliptical. The light profile of this galaxy at the three wavelengths studied is consistent with a pure exponential disk (i.e. the structure parameter $n = 1$). It was detected by IRAS. HI was detected by Haynes and Giovanelli (1980). The CO(2-1) and CO(1-0) molecular lines have been detected by Wiklind et al (1995). We were also able to get a weak detection of the CO(1-0) line using the 12 M NRAO telescope.

KIG 89. This is one of the brighter isolated early-type galaxies in the KIG. It is a very disky elliptical. The disk can be easily seen in the residual image. It was detected at 100μ by IRAS, but no other ISM signature has been found for this galaxy. It is one of the best cases for an isolated ET. A bright star deforms the isophotes at large radius.

KIG 120. This is definitely a spiral. Haynes and Giovanelli (1980, 1984) found HI in this galaxy. Duprie and Schneider (1996) searched for HI extended emission but were not able to detect it.

KIG 128. This is definitely a spiral. It is listed as S0 in the NED. Haynes and Giovanelli (1980, 1984) detected HI in this galaxy. It was also detected by IRAS (Knapp et al. 1989).

KIG 179. This appears to be an E galaxy.

KIG 248. Classified as E by most sources. It has merger signatures, particularly a system of shells. It was detected by IRAS.

KIG 303. This is an S0 galaxy with a prominent disk. Haynes and Giovanelli (1984) searched for HI in this galaxy, but they were not able to detect it.

KIG 308. It is classified as E by Karachentseva, as well as in the NED. But it is definitely a spiral with strong arms. It was detected by IRAS.

KIG 358. This galaxy could be considered as a good example of an isolated elliptical. However, at least 2 supernovae have been observed in this galaxy: SN 1993C was recognized as a SN IA. But SN 1993E presented the H_α emission characteristic of SN II supernovae. Several small galaxies can be seen close to KIG 358.

KIG 393. It was classified as an early-type by Karachentseva, but it is now classified as Sb in the NED.

KIG 396. This appears to be an elliptical. It is surrounded by many faint objects.

KIG 437. It is classified as E? in the NED. It appears to be correctly classified, but the image in Appendix A is faint.

KIG 443. It is classified as S0 in the NED. It is more likely a spiral, but it is quite faint to be certain.

KIG 467. It is classified as SB0 in the NED.

KIG 501. It is classified as E? in the NED. We can see faint traces of spiral structure.

KIG 503. This galaxy has been classified as elliptical in the past. But it has a double nucleus, suggesting a merger of two or more galaxies. It has also been detected by IRAS.

KIG 505. It is classified as SAab in NED.

KIG 511. It is listed as an S0 in the NED. The S/N for this galaxy is quite low. However, a conspicuous filament, probably due to a spiral arm is observed, suggesting that this is a late-type galaxy.

KIG 537. It is classified as a compact galaxy in the NED. It is probably an Sa. There is a filament that could be a faint spiral arm. A higher S/N image is needed to verify the morphology.

KIG 555. It is classified as E in the NED. It is definitely not a normal elliptical. It could be a perturbed E or perhaps even a spiral. It has a filament that looks like a jet, that could be a spiral arm or maybe even a tidal tail, but better data is needed.

KIG 633. It was classified as E in the KIG. It is definitely a spiral with strong and well defined arms. The outer arm is very extended. It was detected by IRAS.

KIG 697. It is classified as SB0 in the NED. It was detected in HI by Haynes and Giovanelli (1984).

KIG 705. It is classified as E in the KIG, and as an E? in the NED. However, faint traces of spiral structure are seen on the B image.

KIG 714. It was classified as early-type by Karachentseva, but is classified as Sa in the NED. It is probably an Sbc galaxy.

KIG 721. It is classified as E in the KIG as well as in NED, It is probably a spiral but the arms are not well defined due to poor S/N.

KIG 732. It is classified as E with a compact core.

KIG 768. It is classified as E in the KIG. But it has several characteristics of a merger. In fact, it bears a close resemblance with NGC 3656, which is a well known merger (Balcells & Standford 1990). It has shells and it was detected by IRAS (Knapp et al. 1989). Haynes and Giovanelli (1984) detected HI in this galaxy.

KIG 798. It is classified as E? in the NED.

KIG 824. It is classified as E in the KIG. A very faint arm is seen on the B image.

KIG 829. It is classified as E in the KIG and E? in NED. It is a very blue compact object. It was detected by IRAS. It is more likely a merger. It is highly asymmetrical, and resembles images of mergers obtained by theoretical simulations (Weil & Hernquist 1996).

KIG 841. It is also called NGC 6524. It was classified as an early-type by Fich and Hodge (1993). But the image of KIG 841 in Appendix A presents clear spiral arm features. It was detected by IRAS at all wavelengths. Huchtmeier detected HI for this galaxy. CO(2-1) has been detected by Knapp & Rupen (1996). Fich & Hodge (1993) found a large quantity of dust in this galaxy.

KIG 894. It is classified as E in the NED. But it might be an example of two galaxies undergoing a merger event. If this interpretation is correct, the nuclei of the galaxies are still apart, but the arms (or tidal tails) are interlaced. The 2 interlaced rings have the form of a number 8. It was detected by IRAS, and evidence for dust is found from this work. It has never been studied in detail, the only two references are that of the KIG, and the redshift measured by Huchra et al. (1999) for the CFA Survey.

KIG 1015. It is classified as E in the KIG, and as E? in the NED. But the morphology is very perturbed. It is also quite compact. HI was detected by Haynes and Giovanelli (1980, 1984).

KIG 1045. It is classified as E5-6 in the NED. It is one of the brightest galaxies in the KIG sample. It is mostly boxy, but it also has a well defined local peak in C_4 at ~ 31 arc sec. This peak is seen at the three wavelengths studied.

• Comments for Galaxies from the Fasano and Bonoli Sample

UGC 5705. Better known as NGC 3265, is the most perturbed early-type galaxy in the F&B sample (see Appendix A). It was detected by IRAS at 60 and 100 μm (Knapp et al 1989). HI was detected by Huchtmeier et al (1995). Wiklind et al. (1995) detected molecular gas through CO (2-1) transition. Dust continuum

emission has been detected by Fich and Hodge (1993), and by Wiklind and Henkel (1995).

UGC 6159. It is also known as NGC 3522. This is an elliptical with a disk component. Evidence for the disk is seen from the C4 profile, as well as in the image. It is also known as NGC 3522.

UGC 6504. It is also known as NGC 3710. This is a nearly featureless elliptical galaxy. The harmonic amplitudes hardly deviate from zero. The P.A. is almost constant.

UGC 6810. It is also known as NGC 3919. This elliptical appears to contain dust. Small dust signatures are seen on the S3 coefficient as well as in the residual image. No structural features are seen on the C4 profile.

UGC 7115. This is a very spherical elliptical galaxy. No strong features are seen in the residual image or the harmonic amplitude.

UGC 7681. This is an elliptical with a small disk component. No strong component of dust is seen on the third order profiles.

UGC 7767. This is an E0 galaxy. The unusual behavior of the ellipticity and P.A. profiles is seen at both *B* and *I* bands, therefore it must be real (compare also with the results of Fasano and Bonoli 1989). However, the two spots that appear to be due to dust in the residual image are spurious. They are probably due to features on the CCD.

UGC 9070. It is also known as NGC 5500. It is an almost featureless galaxy. The

surface brightness profile is well fitted by a de Vaucouleurs law.

UGC 9278. It is also known as NGC 5628. As for the case of UGC 9070, it is well fitted by a de Vaucouleurs law. But in contrast with UGC 9070, this galaxy does present faint structural features (weak spiral arms?).

UGC 10352. It is also known as NGC 6172. It was detected by IRAS (Knapp et al 1989). The S3 harmonic amplitude reveals the presence of dust in this galaxy. A very small disk component is seen on C4.

• Comments for Galaxies from the HCG Sample

HCG 10b. This E1 galaxy is also known as NGC 529. Pildis et al. (1995) claimed that it has an off-centered (from the bright core of the galaxy) sharp edged shell that completely surrounds the galaxy, and that the residual light has a prominent bright column that extends to the north of the galaxy core. The shell can be seen in the direct *B* in Appendix A. The shell has a rough edge. In other words, it does not have the perfect elliptical shape seen in shells in many ellipticals. We also observe in the residual images the column Pildis et al. (1995) refer to. But in our case that column is only part of an “X” pattern (see Appendix A).

HCG 34a. This galaxy is also known as NGC 1875. It is classified as E2 in the NED. No major structural features are found for this galaxy.

HCG 37a. This galaxy is also known as NGC 2783. It was classified as E7 by Hickson (1989), but it is classified as S0+ in the NED. The negative value of the *C*4 coefficient indicates that it has boxy isophotes. A structure of shells has been confirmed by this work (see the direct B-band image in Appendix A). WCH

searched for CO in this galaxy, but were only able to get limits for the H_2 mass of $7 \times 10^8 M_\odot$.

HGC 40a. This galaxy was classified as E3 by Hickson (1989). It is the brightest galaxy in HGC 40, which is the same group as Arp 321 (Arp 1966). The positive value of C_4 indicates that it is disk. It was detected by IRAS.

HGC 40b. This galaxy was classified as S0 by Hickson (1989). The negative value of C_4 indicates that it is boxy. The image suggest that it is interacting with its two nearest neighbors. An extensive discussion of the HCG 40 compact group is given by Bettoni & Fasano (1993). They argue that HGC 40b is in an intermediate stage of a merging process.

HGC 61a. This is NGC 4169. It was classified as S0a by Hickson. The residual image in Appendix A shows the presence of spiral structures, and possibly of a bar.

HG 68a. This is galaxy NGC 5353. It was classified as S0 by Hickson. The C_4 profile as well as the image indicate that this galaxy is disk. It was detected by IRAS.

HGC 68b. This is galaxy NGC 5354. It was classified as E2 by Hickson. Mendes de Oliveira & Hickson (1994) reported a strong dust lane in this galaxy. Our data confirms the presence of this dust lane.

HGC 68d. This is galaxy NGC 5350, classified as E3 by Hickson. Mendes de Oliveira & Hickson (1994) claim that this is a boxy galaxy, and that it probably have shells. Our surface photometry results do not support the claim of boxiness.

The optical (Fig. 3.35) and infrared (Fig. 4.36) profiles tells us that $C4 \sim 0$ up to a semi-major axis value of ~ 25 arc sec. Beyond this isophote, $C4$ has a small positive value. On the other hand, we also find evidence for a shell located to the W-NW of the galaxy (note: the horizontal line in the I-band image shown in Appendix A is due to a bad pixel column, not to saturation).

HGC 82a. It is also known as NGC N6162. It is an E3 galaxy (Hickson et al. 1989). It is neighbor to HGC 82b (NGC 6163), which was classified as SBa by Hickson.

HGC 93a. It is also known as NGC 7550. It was classified as E1 by Hickson et al. (1989). Pildis et al. (1995) presented evidence for shells and for two spokes extending to the west and to the southwest of this this galaxy. Our direct I-band image (Appendix A) confirm that this features are real.

• Comments for the ISM Detected Galaxies

NGC 759. At the level of resolution of the images in this work, this galaxy appears to be well classified as an E0. The residual image presents faint structures close to the nucleus. It is one of the brightest galaxies of the A262 cluster (WCH). It constitutes a noninteracting pair with NGC 0753 (at 23.5 arcmin). Feretti and Giovannini (1994) found diffuse radio emission, with a central peak, but without a central core. Following Wrobel & Heeschen (1988), they claim that the radio emission is due to star formation. It was clearly detected at CO(1-0) and CO(2-1) by WCH, from which they found a rotating ring with $2 \times 10^9 M_{\odot}$ of H_2 . From the properties of the molecular gas and current star formation Wiklind et al. (1997) suggest that NGC 759 is a late stage of a merger between 2 gas rich disk galaxies.

NGC 807. This is a relatively isolated galaxy. It has been considered to be a dusty E3 galaxy, however, we observe signatures of spiral arm structures at small and large scales for this galaxy. The residual image presents considerable structure close to the nucleus. It was detected by IRAS at $60\mu\text{m}$ and $100\mu\text{m}$ by Knapp (1989). It has also been detected in HI by Huchtmeier (1996), and was observed by Dressel (1986) and Dressel (1987) at both Arecibo and at the VLA. She concluded that it is a quiescent giant elliptical with a large mass of $6.2 \times 10^9 M_{\odot}$ of neutral hydrogen in a normal disk. WCH detected CO(1-0) and CO(2-1), and were able to derive a mass of H_2 of $1.9 \times 10^9 M_{\odot}$.

NGC 855. It is classified as elliptical in the RC3. In some references it is classified as a dE (dwarf elliptical). At large radius it looks like a very elongated elliptical (in the POSS plates it appears to be an E7) galaxy, but the isophotes in the inner regions are definitely not ellipticals. This can be seen in the direct image as well as in the residual image. Phillips et al. (1996) presented a deconvolved image of this galaxy taken with the original Planetary Camera of the Hubble Space Telescope. They found that the inner structure “clearly shows features of an edge-on late-type galaxy”. They find no clear central concentration, but rather a string of several bright knots as well as a patchy dust distribution. They suggest that the knots are due to globular clusters, but cannot rule out the presence of point sources. They also note that the P.A. of the line of knots is $\sim 90^\circ$ which is very different from the P.A. of $\sim 65^\circ$ of the outer isophotes. From the 90 inch images we can verify several of their findings. NGC 855 was detected by IRAS at $60\mu\text{m}$ and $100\mu\text{m}$. It has been mapped in HI by Walsh et al. (1990) using the VLA. They found the presence of a rotating disk with an H I distribution highly inclined with respect to the optical semi major axis. Wrobel & Heeschen (1989) found an extended source at 6 cm

observing with the VLA, which has been suggested to be due to star formation. Very narrow emission lines of CO(1-0) and CO(2-1) have been detected by WCH.

NGC 2128. This is an elliptical with a dust lane. It was detected by IRAS (Knapp et al. 89). Huchtmeier (1995) was not able to detect HI.

NGC 2320. This is a dusty E4 galaxy in A569. It was detected by IRAS at $60\mu\text{m}$ and $100\mu\text{m}$. Neutral hydrogen was not detected by Huchtmeier (1995). CO has been only weakly detected by WCH, from which they infer $\text{MH}_2 = 7.0 \times 10^9 \text{ M}_\odot$. Wiklind and Henkel (1995) searched for dust from the mm continuum emission at $1250 \mu\text{m}$.

NGC 2534. This is classified as E1. It has a very pronounced dust lane that extends over a sizable fraction of the galaxy (Ebner and Balick 1985). HI was detected by Huchtmeier et al. (1995). CO(1-0) detection has been claimed by Wang et al. (1992) observing with the Nobeyama telescope, but WCH were not able to confirm it.

NGC 2672. This is an early-type galaxy that forms part of an isolated pair of galaxies with NGC 2673 at 0.6 arc min. The pair is also known as Arp 167 (Arp 1966). According to the classification given by Arp these galaxies have “diffuse counter-tails”. It was detected in HI by Huchtmeier (1994).

NGC 2768. This is a relatively isolated galaxy classified as E6. The patchy distribution of dust can be clearly seen in the residual image to be distributed along the minor axis, but there also appears to be a more extended uniform distribution of dust along the major axis. The *I* image was taken on a night with exceptionally

good seeing. For this reason, it reveals the dust structure in greater detail than in the B image (which has a higher S/N). Besides, the I image also shows a system of what appear to be globular clusters. CO(1-0) and CO(2-1) have been only weakly detected by WCH. CO(2-1) has been only tentatively detected by Lees et al. (1992).

NGC2810. This galaxy was detected by IRAS at $60\mu\text{m}$. Huchtmeier et al. (1995) detected HI. A late-type galaxy close in angular distance to the nucleus can be seen in Appendix A. This galaxy was not detected by IRAS at $100\mu\text{m}$, and no CO detection has been reported for it. However, this is an interesting object because it is the only bona fide elliptical without any peculiarity among the detected early-type sample.

NGC 3597. This galaxy used to be classified as Elliptical in the past. But, it is now known to be a merger remnant (e.g. Wiklind & Henkel 1995). It is one of the most luminous IRAS galaxies. It has a flux density at $60\mu\text{m}$ of 10 Jy, which implies a $60\mu\text{m}$ luminosity about 10 times higher than what is typically found in normal spiral galaxies. Taniguchi et al. (1990) found that the luminosity profile of NGC 3597 follows the de Vaucouleurs $r^{1/4}$ law well, thus they presented this as a merger candidate. Further evidence for a merger was presented by Lutz (1991). He concluded that NGC 3597 will evolve into a featureless elliptical galaxy of moderate luminosity. The excess of FIR luminosity is presumably due to enhanced star formation activity. CO(1-0) has been detected by van Driel & van den Broeck (1991), and by WCO. WCO infer a mass of H_2 of $3.9 \times 10^9 M_\odot$.

NGC 3656. This is also known as Arp 155 (Arp 1966). This galaxy has been thoroughly studied, and it is considered to be a merger (Balcells 1997). It has

been classified in the past as a non-magellanic irregular or a face on S0 galaxy, and as an Elliptical. It was already shown from the infrared data of Balcells & Stanford (1990), that NGC 3656 is a very disturbed galaxy. It has a dust disk, a counter rotating core, and several shells. Some of these features can be clearly seen in Appendix A. The faint objects surrounding NGC 3656 are thought to be dwarf galaxies. HI has been detected by Haynes & Giovanelli (1991). Both CO(1-0) and CO(2-2) transitions have been detected by WCH.

NGC 3928 (MRK 0190). It is classified as an E0 in the UGC catalog (Nilson 1973). It is thought to contain a starburst nuclei (Balzano 1983). It definitely has spiral structure (see Appendix A). HI has been detected by Thuan & Martin (1981), Jackson et al. (1989) detected the CO(1-0) transition, obtaining a H_2 mass of $1.0 \times 10^8 M_{\odot}$. Finally, Fich & Hodge (1993) determined limits to the amount of dust.

NGC 5666. This is a fairly isolated galaxy, usually classified as Elliptical or as Ep (peculiar elliptical). According to this work it has spiral structure. But the most striking feature is the complex structure surrounding the nucleus, where it presents multiple (approximately 7) bright knots surrounding the nucleus. These features can be easily seen in the B-image, where unlike the I-band image the central nuclear spot is not the brightest, indicating the effect of dust extinction. Due to this network of bright spots, the brightness profile of this galaxy is very flat out to a large distance from the center of the galaxy. In fact, it has the flattest profile among all galaxies in this thesis. It has been mapped at 6 cm with the VLA by Wrobel & Heeschen (1988), from which they suggested that NGC 5666 is currently forming stars. The radio continuum emission data was later combined with the far-infrared emission by Walsh et al. (1989), from where they deduced that the

active radio nucleus is due to a black hole being fueled by gas accretion. HI has been detected by Huchtmeier et al. (1995). WCH have detected CO, and dust has been detected by Wiklind & Henkel (1995). This galaxy definitely deserves to be studied in more detail in the future.

NGC 6166. This is the dominant cD galaxy with multiple nuclei in the Abell 2199 cluster.

NGC 6702. This is an isolated elliptical galaxy with a dust lane along the minor axis. The structure of the dust lane can be seen very clearly on the residual image in Appendix A. Despite the dust lane and a FIR flux at $100\mu m$ (Knapp et al. 1989) of 2.4 Jy, it has not been possible to detect CO emission in any transition (Wang et al. 1992, WCH, Knapp & Rupen 1996). Likewise, Huchtmeier et al. (1995) only obtained a tentative detection for H I. Knapp & Rupen (1996) comment that the $100\mu m$ emission is probably due to cirrus in the Galaxy.

NGC 7052. This is a fairly isolated E4 radio galaxy with a nuclear disk of dust and gas, that is thought to harbor a black hole in its nucleus (van der Marel & van den Bosch 1998). Surface isophote analysis has been previously done by Bender et al. (1988). The dust lane, which is oriented along the optical major axis has been observed by NICMOS (Quillen et al 2000). Since it is within a few (2-3) arc seconds from the nucleus, no clear evidence of the lane is seen by this study. It has been detected at HI by Huchtmeier et al. (1995). Wang et al. (1992) reported a detection of CO(1-0) emission, but WCH could not confirm the CO detection.

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