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OPTICAL ANALYSIS OF AN
X-RAY SELECTED SAMPLE OF STARS

by
Thomas Anthony Fleming

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

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SIGNED: Thomas A. Fleming

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ABSTRACT

I analyse an x-ray selected sample of 128 late-type (F-M) stars. These stars were identified as optical counterparts to serendipitous x-ray detections made by the *Einstein* Observatory Extended Medium Sensitivity Survey. Once identified as x-ray sources, the stars were reobserved with an extensive program of optical observations consisting of high- and low-resolution spectroscopy and photometry. Spectral types, luminosity classes, absolute magnitudes, distances, x-ray luminosities, projected rotation rates ($v \sin i$), radial velocities, and binary status have been determined for the sample.

I find that L_x is correlated with $v \sin i$ for single stars. However, L_x does not correlate with $\Omega \sin i$, which leads me to believe that the correlation seen with $v \sin i$ is actually a correlation with radius. Indeed, L_x correlates strongly with radius (color, mass) for main sequence stars. This result provides a plausibility argument for rotational saturation in the coronae of late-type stars.

Since this sample is flux limited, I use sky coverage and sensitivity information from the *Einstein* Observatory to calculate the bright end of the x-ray luminosity function for late-type stars. It appears that previously calculated luminosity functions from optically selected samples have underestimated the number of x-ray bright F and G dwarfs. I have also discovered 8 previously uncatalogued M dwarfs within 25 pc of the sun.

My sample includes only M dwarfs of spectral type M5 and earlier, 93% of which are “emission” stars (i.e. type Me V), as well as two pre-main sequence M stars. Arguments involving kinematics and stellar rotational velocities are used to estimate the age of these x-ray “bright” M dwarfs; they

appear to be quite young ($\leq 1-3 \times 10^9$ yrs). Since the local space density of x-ray “bright” M dwarfs increases with mass, I infer a longer activity timescale for lower masses. M dwarfs later than M5 lie below the sample’s x-ray sensitivity limit. An upper limit of $\log L_x = 27.45$ is put on their coronal emission.

I also present H_α and Ca II K line fluxes for most members of the M dwarf sample and show that the H_α and Ca II K luminosities do indeed correlate with L_x . However, these chromospheric luminosities are weaker functions of rotation than L_x and may, in fact, represent saturated levels of activity. My results are consistent with the hypothesis that the chromosphere is heated by x-rays from the overlying corona.

Finally, I discuss two unusual members of the sample which are attractive candidates for the recently proposed class of FK Comae stars.

Chapter 1

Introduction

Stellar X-ray Emission

Fifteen years ago, if a graduate student had suggested doing a Ph.D. dissertation on the topic of stellar x-ray emission, he/she would have been reminded about the minimum page requirement for theses. After the advisor had finished laughing, the student would have been reminded that, except for a few exotic objects, cosmic x-ray sources originated from outside of the Galaxy. Our understanding of the topic has come a long way in little more than a decade. With the advent of the *Einstein* and *EXOSAT* Observatories, astronomers have discovered that stellar x-ray emission is not the exception, but the rule. The current state of this subject was recently summarized in an excellent review article by Rosner, Golub, and Vaiana (1985).

Fig. 1 is reproduced from Rosner, Golub, and Vaiana (1985). It illustrates all known areas of x-ray activity across the Hertzsprung-Russell (H-R) diagram. I will briefly consider each portion of the diagram and summarize the astrophysical theories on how the x-rays are (or are not) generated.

The first region which I will consider is the main sequence from spectral type F to M together with giants (luminosity class III) earlier than K2. Stars in this region of the H-R diagram have convective outer envelopes and are believed to emit x-rays by the same process. The x-radiation itself is emitted via thermal bremsstrahlung from a 1 to 20×10^6 K plasma, called the corona, which

Figure 1. Representation of x-ray activity on the Hertzsprung-Russell diagram. The shaded areas indicate those classes of stars known to emit x-rays. This figure is reproduced from Rosner, Golub, and Vaiana (1985).

constitutes the outermost layer of the stellar atmosphere. It is not unusual that a million degree plasma would emit x-rays. The mystery is how the corona was formed in the first place. Simple thermodynamics suggests that as one moves away from an energy source, in this case the stellar core, the temperature should steadily decrease. There must be some non-radiative process at work which efficiently heats the outermost layers of a star's atmosphere to create a corona (and a chromosphere).

One promising idea was that these outer layers were heated acoustically from the deposition of mechanical energy by photospheric convection cells (granulation) and turbulence. This idea is not valid, however, since acoustic heating models can not account for the amounts of energy released by coronae and chromospheres. Furthermore, these same models also predict a large dependence on g and T_{eff} which is not seen in coronal emission, and that coronae so formed should be homogeneous, which is also not observed (cf. Ulmschneider 1986).

The currently favored model of coronal formation involves magnetic heating and the generation of the magnetic ($\mathbf{B}$) field through some sort of dynamo (Parker 1979). Differential rotation which is experienced at the base of the convection zone is responsible for generating toroidal $\mathbf{B}$ field from the originally primordial poloidal $\mathbf{B}$ field (the Ω -effect). Due to magnetic buoyancy, these newly generated toroidal fields float to the surface of the star. While toroidal $\mathbf{B}$ fields are rising through the convection zone, turbulent motions caused by the coupling of rotation and convection induce the generation of poloidal $\mathbf{B}$ field from the toroidal field (the α -effect). Poloidal $\mathbf{B}$ field created by the α -effect will then prompt the generation of more toroidal $\mathbf{B}$ field via the

Ω -effect. In this way, the dynamo can “feed” itself. When the toroidal B field reaches the stellar surface, it is still embedded in the convection zone fluid, so it is jostled by the turbulent surface motions. This “jostling” can cause plasma heating and form a corona which is confined to the emergent magnetic fields. This entire process is explained in great detail in a review article by Kuperus, Ionson, and Spicer (1981). Such a process will form an inhomogeneous corona whose strength will depend on stellar rotation rate and convection zone depth.

This region of the H-R diagram also includes the “active” binaries (e.g. RS CVn and W UMa types). Although the same mechanism for x-ray production is thought to apply here, these binaries emit x-rays at substantially enhanced levels over single stars having the same characteristics as the binary components (Charles 1983; Dupree 1983).

Also represented in this region of the H-R diagram are the pre-main sequence (PMS) stars. These objects are strong x-ray sources having luminosities on the order of a thousand times greater than main sequence stars of the same spectral type. However, PMS x-ray emission is extremely variable, not linked to other activity indicators, and intrinsically (i.e. allowing for circumstellar absorption) harder than normal stellar x-ray emission. Astronomers are still uncertain about the origin of PMS x-ray emission (Feigelson 1984).

The upper right-hand corner of the H-R diagram is void of x-ray emission. No giants (III) later than type K2 and supergiants (I) later than G0 have ever been detected in x-rays (Haisch and Simon 1982; Haisch 1988). This, along with similar results in the ultraviolet, have prompted the drawing of the so-called “Linsky-Haisch” dividing line across the H-R diagram. Stars which lie to the right of this line do not display coronal or chromospheric ac-

tivity. There are several ideas concerning the lack of x-ray emission from the coolest, evolved stars. The first to be suggested was that the entire surface of a red giant was covered with open magnetic field structures, as evidenced from the large mass-loss rates of these stars. The solar wind escapes along such open field structures in certain regions on the Sun, called "coronal holes". No x-rays are detected from these areas.

This explanation was somewhat unsatisfying since it left one then to explain why the entire surface of a red giant should be a gigantic coronal hole. A more reasonable explanation has been offered by Antiochos and Noci (1986). These authors have identified a new class of magnetic loop solutions. These closed loop configurations are cool ($T < 10^5$ K), but they are only stable at low surface gravities (viz. red giant gravities). Therefore, Antiochos and Noci suggest that red giants do form coronae in the same manner as late-type main sequence stars, but red giant coronae have temperatures less than 10^5 K, which means that they can not emit x-rays.

An alternative explanation has been given by Böhm-Vitense (1986). She suggests that a corona is not formed in red giants because of a simple scale height effect. A chromosphere is formed from the deposition of mechanical energy from below. This input energy is balanced by energy lost through radiation. However, as one moves further out from the star, the electron density decreases, which means the temperature must increase in order to radiate away the same energy. Finally, the temperature will reach 15,000 K, at which point hydrogen ionizes, energy balance is lost, and a hot corona is formed. Now since red giants have lower surface gravities, their electron pressure scale heights will be bigger than those of dwarf stars. If the dissipation length for

the mechanical energy flux is less than half the electron pressure scale height, then the mechanical input energy which would form the corona will dissipate before the electron density becomes low enough (and temperature high enough) for hydrogen to ionize. Böhm-Vitense estimates that this condition is met in red giants.

The final region of strong x-ray activity in the H-R diagram involves the O and B stars. The x-ray luminosity of these stars is strictly a function of bolometric luminosity. This and the fact that these stars have radiative outer envelopes and large mass-loss rates suggest a radically different x-ray emission mechanism than the one for late-type stars. This mechanism is not well understood. The current best guess (Lucy and White 1980) is that the massive, radiatively-driven winds from these stars could be unstable. This instability might cause higher-density blobs of matter to form which would initiate shock-fronts throughout the unstable region of the wind outflow. The shock-heated material would emit x-rays. However, at present, no model of O and B star x-ray emission comes close to explaining the observations (Rosner 1986, private communication).

Along the main sequence, there is a narrow gap (B8–A5) where no credible x-ray detection has been made of a normal star (Ap stars have been detected; Schmitt *et al.* 1985a). The obvious observation to make here is that this is the region where main sequence stars switch from having radiative envelopes to having convective envelopes. These stars may be in some intermediate state where it is impossible for either the early- or late-type x-ray emission process to operate.

The last blank region in the H-R diagram of Fig. 1 is the lower left-hand corner, which is the realm of the degenerate stars. The x-ray detections of cataclysmic variables and x-ray binaries are not indicated in Fig. 1, since these objects are rarely included in discussions of stellar x-ray emission. The x-ray emission process from these objects is non-thermal and occurs when matter from the secondary is accreted onto the degenerate surface of the primary.

However, while two different mechanisms have been suggested for x-ray emission from single white dwarfs, very few have actually been detected. Böhm and Cassinelli (1971) predicted that the deposition of mechanical flux from convective cells in the envelopes of helium-rich (DB) white dwarfs should acoustically heat the outer layers of these stars. Therefore, hot DB white dwarfs should have coronae. Later models (Muchmore and Böhm 1978) showed that coronal temperatures would range from $10^6 - 10^7$ K. A survey of 10 DB white dwarfs conducted with the *Einstein* Observatory failed to detect any positively (Fontaine, Montmerle, and Michaud 1982). These authors placed upper limits on DB x-ray luminosity which indicate that white dwarf coronae, if they exist, are not as strong as their main sequence analogs.

Shipman (1976) predicted that single DA white dwarfs should also be x-ray sources. Since these stars have very thin, hydrogen-rich envelopes, their photospheres would be transparent to x-rays. Therefore, one should observe thermal x-ray emission from the hot white dwarf core. Only 5 such stars were detected with the *Einstein* Observatory (Petre, Shipman, and Canizares 1986; Kahn *et al.* 1984). Another 11 were detected by EXOSAT (Paerels and Heise 1988). It was expected that He in the atmosphere would absorb the x-rays.

The fact that most hot white dwarfs are not x-ray sources indicates that there is more He in the atmospheres of the DA stars than was first thought.

The Dissertation Project

Our knowledge of stellar x-ray emission, as presented in the previous section, depends on one assumption. Namely, that the stars selected for study are representative of all stars as a whole. The conclusions which have been drawn are based upon results of pointed observations and optically selected surveys. I quote Rosner, Golub, and Vaiana (1985) regarding the controversy over the precise relation between x-ray luminosity and rotation period in late-type stars: “...but it appears that the fundamental difficulty (which remains in place to date) is the introduction of possibly large biases because of the ill-defined nature of the various samples of stars for which both rotation rates and x-ray luminosities are known. ”

Another problem which is related to the one mentioned above is that most astronomers who study stellar x-ray emission are either x-ray astronomers or theorists. Therefore, they must rely on whatever optical or infrared data is already in the literature. This adds to selection biases. Furthermore, the optical data used in x-ray studies are rarely uniform since they come from a variety of sources.

Given these difficulties, I decided to undertake a dissertation project which would attempt to alleviate some of them. I am working with x-ray sources which were serendipitously detected by the *Einstein* Observatory. By

using an x-ray selected sample of stars, I hope to eliminate the selection biases mentioned above. Of course, I am replacing one bias with another. But all that means is that I can not study moderate to low levels of stellar x-ray activity. I can study high levels of stellar x-ray activity in an unbiased manner since my sample is truly representative of the brightest stellar x-ray sources.

In addition, this project is the first one, to my knowledge, to take a homogeneous set of stellar x-ray detections and then to obtain a homogeneous and extensive set of optical observations of the entire sample. Using both high and low resolution spectroscopy and photometry, I have derived such stellar parameters as spectral type, luminosity class, distance, binary status, rotational velocity, and degree of chromospheric activity.

The amount of science which can be done with this massive database is too great for one dissertation. I have, therefore, had to leave some topics out. I will not discuss the cataclysmic variables or the B and A stars which are in my sample. A detailed analysis of the new RS CVn and W UMa binaries which I have discovered, as well as a few oddities, must be postponed to another day. I believe that the greatest contribution this dissertation will make to astronomy is the presentation of its data. I have taken care to document the observations and compile all of them in the Appendices so that they may be of use to others.

Chapter 2 will describe the details of the acquisition, reduction, and analysis of all data which are compiled in the Appendices. Chapter 3 treats the topic of the relation between x-ray luminosity and stellar rotation. Chapter 4 presents an x-ray luminosity function for the x-ray brightest late-type stars which was derived from my flux limited, x-ray selected sample using the sky

coverage and flux sensitivity information from the *Einstein* Observatory. Chapter 5 is devoted entirely to the M dwarfs. Chapter 6 discusses two particular stars which are candidates for the rare class of FK Comae stars.

CHAPTER 2

The Database

In this chapter, I describe in detail the x-ray and optical observations of which the database is composed. The database itself is presented in tabular form in the Appendices. Since this dissertation involves the study of an x-ray selected sample of stars, I will begin with the observations which define the sample.

Einstein Observatory Imaging Proportional Counter Observations

The serendipitous x-ray detections which are used in this dissertation were made by the *Einstein* Observatory Imaging Proportional Counter (IPC). The IPC was a soft x-ray (0.15 - 4.0 keV), high efficiency, position sensitive proportional counter. It covered a wide field of view (1 square degree) with modest resolution, both spatial (~ 1 arcmin) and spectral ($E/\Delta E \sim 1$). The instrument itself consisted of an anode wire plane centered between two cathode wire planes inside a chamber which was filled with an Ar-CO₂-Xe gas mixture. The basic principle behind the instrument's operation is as follows. The x-ray photons which have been collected and focused by the telescope enter the chamber through a 2 μ m-thick polypropylene window. The x-ray photons then proceed to ionize atoms of the gas. The resulting avalanche of free electrons collect at the anode and ions travel to the cathode grid, which induces a current signal (pulse) on the cathode. Each pulse detected corresponds to an x-ray photon and the pulse height (strength) is proportional to the energy of the photon. The sophisticated electronics which process these signals can determine the spatial position of each detection.

The x-ray selected sample of stars defined in this dissertation was taken from the *Einstein* Observatory Extended Medium Sensitivity Survey (EMSS; Gioia *et al.* 1987). This survey involved the reprocessing of 1435 IPC exposures with an improved detection algorithm (REV1; Harnden *et al.* 1984) in order to discover serendipitous x-ray sources. The center of each IPC frame (circle having a 5 arcmin radius together with the target object) associated with a pointed observation was excluded from the sample in order to avoid any selection biases that might result from various guest observer programs. The term “Medium Sensitivity” refers to the fact that the limiting x-ray fluxes of the IPC observations which were used in the EMSS ranged from 7×10^{-14} to 2×10^{-12} ergs cm $^{-2}$ s $^{-1}$. These sensitivities were intermediate between the *Einstein* Deep Survey (Griffiths *et al.* 1983; Giacconi *et al.* 1979) and the HEAO-1 all-sky survey (Piccinotti *et al.* 1982). The limiting flux is a function of exposure time and varies from spot to spot across the IPC frame. Also, in an effort to avoid regions of high Galactic absorption and to minimize the number of optical counterparts in any given positional error circle, only those IPC observations which were taken at $|b^{II}| > 20^\circ$ were included in the EMSS. Finally, the EMSS counted only those detections in the 0.3 - 3.5 keV energy band.

The EMSS contains 836 serendipitous x-ray sources. The size of the sample has greatly increased over the 112 sources previously published in the Medium Sensitivity Survey (MSS; Gioia *et al.* 1984; Maccacaro *et al.* 1982) due to the inclusion of more IPC fields, use of the entire IPC field of view, and the detection of sources down to the 4σ level.

In the next section, I describe the process in which the EMSS sources were identified with optical counterparts. However, once an EMSS source was identified with a stellar object, then the appropriate value of its x-ray flux (f_x) was calculated. I will now describe the method used to derive f_x from the raw IPC data.

The instrument package described above also included a background, anticoincidence counter which was located below the IPC electrodes. This counter provided background rejection for the IPC. After the total number of raw counts was extracted from a source, the background counts were subtracted from it to obtain the net counts. Next, net counts were converted into corrected counts by applying three different corrections. First, the actual number of counts associated with one source is spread out over a finite area of the detector. This spatial distribution of count has been modeled as a Gaussian function and is called the Point Response Function. The 2.4 arcmin square detection cell which was used in the REV1 reprocessing effectively subsamples only the Point Response Function of a detection. Therefore, the net counts are multiplied by a factor of 1.13 to account for the flux which lies outside of the detection cell (i.e. in the wings of the Gaussian). Second, due to small scale imperfections in the *Einstein* Observatory mirrors, a certain fraction of incoming photons are scattered off image. The net counts are multiplied by a factor of 1.18 to correct for mirror scattering. Finally, since x-ray optics require small reflection angles in order to focus x-ray photons, detections made off the telescope's optical axis (i.e. away from the center of the IPC frame), which involve steeper reflection angles, suffer more photon losses. To compensate for this, the net counts are multiplied by a vignetting correction which is

a function of the distance of the detection from the IPC center. This factor ranges in value from 1.0 to 3.5.

Next, the corrected counts are divided by the effective exposure time, corrected for dead time, to get the corrected count rate. Now, in order to convert corrected count rate into f_x , one must assume a distribution of x-ray photon energies, i.e. an x-ray spectrum, since the IPC energy resolution is so poor. For stellar (coronal) x-ray sources, the proper spectrum to assume is a thermal (bremsstrahlung) distribution with metallic absorption lines. Model spectra for such a distribution have been computed by Raymond and Smith (1977). Analysis of *Einstein* Observatory Solid State Spectrometer spectra (Swank 1985; Swank and Johnson 1982) show that stellar coronae have temperatures which typically range from 8×10^5 to 3×10^6 K. In addition, RS CVn binaries and K and M flare stars usually have a second temperature component ranging from 1 to 2×10^7 K. The count rate-to-flux conversion factors derived from the Raymond-Smith models are nearly identical over these temperature ranges. The conversion factor adopted here, 2×10^{-11} ergs cm^{-2} count^{-1} , is well established (Vaiana *et al.* 1981). The f_x was also corrected for any interstellar absorption that was evident from the optical photometry described later in this chapter.

Although most of the EMSS detections involved too few counts to do spectral analyses, a rough indication of the photon energy distribution for each source was obtained by calculating the Hardness Ratio (HR). The HR is defined as

$$HR \equiv \frac{N_h - N_s}{N_h + N_s}$$

where N_h is the number of counts detected in the “hard” energy channel (0.8 - 3.5 keV) and N_s the number detected in the “soft” energy channel (0.2 - 0.8 keV). By arbitrarily dividing the EMSS energy band into two regions, one can estimate the relative “hardness” of the detection.

The IPC data for my x-ray selected sample of stars (f_x and HR) can be found in Appendix B. The complete details of *Einstein* IPC data reduction can be found in Harnden *et al.* (1984). The soft x-ray luminosity (L_x) was computed for each star, once the distance had been computed, assuming isotropic emission. This quantity is tabulated in Appendix G.

Optical Identification of EMSS Sources

For convenience of observation, I have defined a subsample of the EMSS above $\delta = -20^\circ$ for which the IPC data were reprocessed before August 15, 1985. This will not bias the sample, since the order in which the IPC frames were reprocessed was random with respect to stars. This subset includes 809 IPC fields covering 441 square degrees of the sky (56% of the total EMSS) and yielding 471 serendipitous detections. Over a two-year period, I obtained extensive optical spectroscopy and photometry of the 137 stars in this subsample. The Palomar Observatory Sky Survey (POSS) was used to locate optical counterparts within the x-ray position error circle. Error circle diameters typically ranged from 30 to 60 arcsec for most sources. Then, low-dispersion spectroscopy was obtained for as many of these objects as possible in order to identify the most likely x-ray source. A few sources were also observed

with either the *Einstein* High Resolution Imager (HRI) or the EXOSAT. These sources have a positional accuracy of a few arcsec.

The primary criterion for identification was observation of a well-known class of x-ray emitting object (e.g. QSO, BL Lac, AGN, cluster of galaxies, dMe or dKe flare star, RS CVn binary, cataclysmic variable). When more than one star was located within an x-ray position error circle, stars which showed evidence of chromospheric activity (i.e. optical emission lines) or rapid rotation were identified with the x-ray source. When choosing between “normal” stars or “normal” stars and “normal” galaxies, the identification was made on the basis of the f_x/f_v ratio. Previous work on the MSS, for which reasonable identifications were found for 100% of the sources, has shown a dichotomy in apparent magnitude between galactic and extragalactic identifications at $m_v \sim 16$ (Stocke *et al.* 1983; Maccacaro *et al.* 1988). This arises from the fact that f_x/f_v is small ($< 10^{-1}$) for most stellar objects. Therefore, stars dimmer than 16th magnitude generally have x-ray fluxes too faint to have been detected in the MSS.

This criterion can be used with extreme confidence for two reasons. First, the MSS was small enough that all possible counterparts on the POSS were observed spectroscopically. Second, many of the MSS source identifications were confirmed by reobservation with either the HRI or, at radio wavelengths, the Very Large Array (VLA).

To date, 74% of the sources in this subsample have been positively identified with either galactic or extra-galactic objects. Of the 124 sources not yet identified, only 6 have objects in the error box at or brighter than 16th magnitude. The rest have objects fainter than 16th magnitude. I assume

from the previous MSS work that they are probably extragalactic sources. The 6 unidentified sources associated with brighter objects are not positive identifications because f_x/f_v is too high for their spectral type. Thus, these could also prove to have extragalactic optical counterparts. On the other hand, these stars could have unseen M dwarf companions which are the true source of the x-rays, or the stars themselves could have unusually high x-ray luminosities.

Furthermore, there were 5 EMSS sources which had 2 Me dwarfs (not always associated) in the IPC error circle. If both stars were at the same distance and had the same rotation rate, then the x-ray flux was divided between them in proportion to L_{bol} since L_x/L_{bol} is essentially constant for M dwarfs (Ruciński 1984; Chapter 5). If not, the total x-ray flux was assigned to each star and they are marked as upper limits in all tables and figures.

The last two paragraphs illustrate an important *caveat* in using this serendipity surveys. Unless one has an accurate x-ray position, one is never quite sure if one has made the proper identification. Identifications can be made with various degrees of confidence, but the true x-ray detection could still be of an object below the POSS magnitude limit, or an unseen companion, or a combination of flux from more than one source. And by using the f_x/f_v criterion, one eliminates the possibility of making an unusual discovery (e.g. an extremely x-ray luminous, yet otherwise normal looking star). Consequently, one can not make grand statements and hypotheses based on individual objects from this sample. Only when analyzed statistically, based on trends seen in a large number of objects, can this sample be used to draw astrophysical conclusions.

Optical Observations

Once defined, my EMSS stellar subsample was observed extensively at optical wavelengths. A summary of these observations is given below.

- 2 - 5 Å Resolution Spectroscopy
 - assign spectral type
 - look for indications of chromospheric activity
- 0.1 Å Resolution (Echelle) Spectroscopy
 - measure stellar rotation
 - measure radial velocity at several epochs
 - obtain H $_{\alpha}$ and Ca II H & K line profiles
- UBVRI Photometry
 - check spectral type
 - assign luminosity class
 - measure any interstellar absorption
 - derive distances from photometric parallax

In addition to the members of my defined subsample, I also obtained limited optical observations of several EMSS stars which were outside of my subsample (mostly at $\delta < -20^{\circ}$). The results for these stars are listed in each Appendix after my subsample stars. In the next three sections, I describe in detail these observations and the methods used to calculate the various stellar parameters.

Lower Resolution Spectroscopy

Due to the wide range in apparent magnitude of the EMSS stellar sample ($4 < V < 16$), it was necessary to employ several telescopes of various apertures in order to carry out this project. The brightest stars ($V < 10$) were observed at the #2-0.9 m telescope of Kitt Peak National Observatory using the Intensified Reticon Scanner (IRS) spectrograph. The fainter stars were observed at the Steward Observatory 2.3 m telescope on Kitt Peak using the Boller & Chivens spectrograph. The faintest objects ($V > 15$), along with all M and late K dwarfs, were observed at the Multiple Mirror Telescope (MMT) on Mt. Hopkins, AZ using the MMT Spectrograph.

All three spectrographs were of the dispersive type, using gratings to separate the light by wavelength. The detectors in all three cases were one-dimensional Reticon arrays with photon detection provided by blue-sensitive image tubes (Allen *et al.* 1984). A variety of gratings and settings were employed in order to observe the appropriate features necessary for the accurate spectral typing of each star. The basic setting used an 832 lines/mm grating in second order. This afforded 2 Å resolution covering $\lambda\lambda 3800-4700$ at the 2.3 m telescope and 3.4 Å resolution covering $\lambda\lambda 3800-4900$ at the 0.9 m telescope. A 400 lines/mm grating in second order was also used at the 2.3 m telescope. This setting gave 4 Å resolution from $\lambda\lambda 3600-5600$. These settings were of primary importance for spectral typing the B, A, F, and G stars. In addition, all bright stars observed at the 0.9 m telescope had spectra taken of them at 6.9 Å resolution in the region $\lambda\lambda 5000-7000$ using the 832 lines/mm grating in first order.

Since the primary features used for spectral typing late-K and M stars lie in the red portion of the spectrum, these stars were reobserved with the MMT Spectrograph using a 300 lines/mm grating in first order which afforded 5 Å resolution covering $\lambda\lambda 3600\text{--}7600$. This was the same setting used for EMSS identifications of faint objects.

These low resolution spectra were used to assign spectral types to each member of the sample, including stars already catalogued in the SAO and other bright star catalogues. This was important, since the spectral types given in the SAO catalogue were often inaccurate. All spectral types listed in Appendix A were assigned by me. A breakdown of my EMSS stellar subsample by spectral type is given in Table 1.

The Morgan-Keenan classification system (Morgan, Keenan, and Kellman 1943; Boeshaar 1976) was used for all stars. For this reason, I use the terminology “M dwarf” and “Me dwarf” instead of the common “dM” and “dMe” throughout the text since I did not assign Mt. Wilson spectral types. However, following Joy and Abt (1974), the designation “Me” does refer to the Balmer series in emission. In order to get a rough estimate of the type, each star’s spectrum was first compared visually to digital spectra of the standards given in Turnshek *et al.* (1985) and Jacoby *et al.* (1984). Then, the feature ratios defined by O’Connell (1973) and, for M stars by Turnshek (1981), were computed and compared to the standard ratios in order to refine the subtype and determine luminosity class.

The principle features used in determining subtype for the F and G stars were the ratio of H_γ to the G band of CH at 4300 Å and the ratio of the Ca II H & K lines to the higher level Balmer lines. This last ratio was also

Table 1

My EMSS Stellar Subsample
Breakdown by Spectral Type

	B	A	F	G	K	M
III	...	...	...	4	3	...
IV	...	...	3	3	7	...
V	3	4	32	25	19	31
VI	...	...	...	...	1	...
Total	3	4	35	32	30	31

Number and Type of Binaries

Binaries	RS CVn	W UMa	Ke	Me	CV	PMS
49	16	6	4	4	2	1

the chief discriminant for the A and B stars until photospheric temperatures were hot enough for the He I $\lambda 4471$ line to appear. The principle features for the K stars were the ratio of Ca I $\lambda 4228$ to the G band and the strength of the MgH band at 5211 Å. For the M stars, the ratios of bandhead depth to “pseudo”-continuum for TiO ($\lambda\lambda$ 4954, 5448, and 6159), CaH ($\lambda 6385$), and CaOH ($\lambda\lambda 5530$ -5570) were utilized. This last feature is of primary importance at types later than M4. Distinction between luminosity classes was achieved by measuring the strengths of neutral atomic lines (e.g. Na I $\lambda 5890,96$; Mg I $\lambda 5167,73,84$; Ca I $\lambda 4228$) and by the presence of Sr II $\lambda 4077$. Nevertheless, determination of luminosity class by spectral means is usually difficult. I, therefore, relied on the photometry as the primary discriminant of luminosity class.

Four members of the sample have been identified as “naked” T Tauri stars (i.e. pre-main sequence; PMS) by Walter *et al.* (1988). This identification was made using several criteria: 1) location in a known star-forming region; 2) a radial velocity consistent with the Taurus dark cloud; 3) detection of the Li I absorption line at 6707 Å. Three of the four stars were assigned a distance (and corresponding M_V) of 140 pc based upon their projected spatial association with the Taurus dark cloud. The fourth star (1E0255.3+2018) is somewhat odd in that it is not associated with Taurus or any other known star forming region, yet it clearly shows Li I absorption. It was assigned an absolute magnitude which is typical for PMS stars of its spectral type. The PMS stars are subsequently excluded from most of the analysis to follow. However, when discussing chromospheric and coronal emission, they are included in the figures and identified as PMS.

The probability that other members of the sample are also pre-main sequence is quite slim, since none are located in star-forming regions (irregardless of 1E0255.3+2018). One possible exception is 1E0444.9–1000. It is the only M star in the sample which shows no indication of strong chromospheric activity (see Chapter 5). This M0 star was chosen as the x-ray identification over two apparently normal G dwarfs by virtue of its f_x/f_v ratio. While its spectrum exhibits the CaH and MgH features which are indicative of M dwarfs, there are certain spectral peculiarities which differentiate it from the spectra of M0 and M1 standards. In addition, the star's V - R color is about 0.1 mag too blue for its V - I color, which is appropriate for M1 dwarfs. Consequently, the M star which I have identified with 1E0444.9–1000 could lie slightly above the main sequence. The star is located in Eridanus, not far from Orion, yet not near any known star-forming regions.

Echelle Spectroscopy

High resolution (0.1 Å) spectra were taken of the $\lambda\lambda$ 5165-5215 region of all stars in my EMSS subsample. This spectral region is rich in photospheric absorption lines due to Mg I (the b lines), Fe I, Cr I, Ti I, and Ni I. Since chromospheric activity rarely manifests itself in such neutral metallic lines, they are ideal for measuring the global kinematic properties of a star. In particular, these spectra were used to measure the projected stellar rotational velocity ($v \sin i$) and radial velocity (v_{rad}). These observations were made at several epochs for each star in order to look for variations in radial velocity

which are characteristic of short-period, “astrophysical” binaries. In this study, I wish to keep such binaries separate from the single stars.

The bright stars ($V < 10$) were observed at the 1.5 m Tillinghast reflector of the Smithsonian Astrophysical Observatory (SAO) on Mt. Hopkins, AZ. The faint stars ($V > 10$) were observed at the MMT. Synoptic observations to determine the orbital periods of a few suspected RS CVn binaries were carried out at the 1.5 m Wyeth Reflector (SAO) in Harvard, MA. Observations at all three sites were made with nearly identical echelle spectrographs. These spectrographs use a cross-dispersive grating (600 lines/mm) to separate the echelle orders and a one dimensional Reticon array and blue sensitive image tube to detect one order at a time (Latham 1982; Chaffee 1974).

The radial velocities and rotation rates were measured using the cross-correlation technique described by Tonry and Davis (1979). Briefly, if two digital spectra are treated as mathematical functions ($f_\lambda(\lambda)$ and $g_\lambda(\lambda)$) and the mathematical operation of cross-correlation

$$f_\lambda(\lambda) \star g_\lambda(\lambda) \equiv \int_{-\infty}^{+\infty} f_\lambda(\alpha)g_\lambda(\alpha - \lambda)d\alpha$$

is performed on them, then the position of the resulting cross-correlation peak represents the shift in λ between the two sets of lines and the width of the peak represents the relative broadening between the two sets of lines. By choosing one spectrum to be a radial velocity standard with an undetectably small rotation rate (i.e. narrow lines), measurement of the position of the cross-correlation peak gives the radial velocity of the other spectrum and its width yields the rotation rate ($v \sin i$).

Since one is trying to measure the shifts and widths between two sets of lines, one should use the same set of lines. Therefore, this technique works best

when the standard spectrum (called the template) is of similar spectral type to the program spectrum. The spectra described above were all cross-correlated with three templates which were taken from Latham (1985): HD 214994 (A V), the Sun (G2 V), and HD 115521 (M2 III). The quality of the correlation can be estimated by measuring the ratio of the correlation peak height to the mean height of random-noise peaks in the correlation function. This ratio is denoted as R . For each spectrum, the correlation yielding the highest R value was used for the kinematic analysis. The best correlation was almost always with the template which was closest to the program spectrum in spectral type. Examples of three such spectra and their correlelograms exhibiting different rotation rates are shown in Fig. 2.

Each radial velocity was calculated by taking the shift in wavelength between the program spectrum and the template and converting it, via the Doppler equation, into a velocity. Then, the velocity was corrected for the earth's projected motion along the line of sight to the program stars, resulting in a heliocentric radial velocity. Because of temperature changes in the telescope chamber, grating and setting changes, and instrument modifications, there are minor shifts in the internal optical alignments of the spectrographs. This causes shifts in the zero-point of the radial velocity measurement. Ideally, the radial velocity measured for a sky (solar) exposure should, by definition, be 0 km/s. However, this is rarely the case. Often, sky measurements yield radial velocities as great as ± 1 km/s. In order to estimate this zero-point shift for a given observing run, IAU radial velocity standards (Bouigue 1973) together with dawn and dusk skies were observed throughout the run and their spectra were cross-correlated against the same templates. The averages of the differences

Figure 2a. Example of a narrow-lined echelle spectrogram centered at 5187 $\text{\AA}$ and its cross-correlation function. This particular example shows an F8 dwarf correlated with the Solar template. The measured $v \sin i < 10 \text{ km/s}$.

Figure 2b. Example of a rotationally broadened echelle spectrogram centered at 5187 Å and its cross-correlation function. This particular example shows a K0 giant correlated with the Solar template. The measured $v \sin i = 50$ km/s. Note the increased width of the cross-correlation peak compared to Fig. 2a. This star is a candidate for the FK Comae class of stars and is discussed in detail in Chapter 6.

Figure 2c. Example of an echelle spectrogram centered at 5187 Å whose lines are obliterated due to extreme rotation. The shallow depressions on the left side are all that is left of the Mg I b lines. In this case, $v \sin i$ can not be measured from the cross-correlation peak width. Instead, $v \sin i$ is estimated by directly fitting the synthetically broadened spectra to the program spectrum. This particular star is AH Virginis, a well-known W UMa binary, and $v \sin i \sim 110$ km/s.

between the standard and measured values for each template were used as the zero-point corrections for the run.

All radial velocities, along with the Heliocentric Julian Date of each observation, are tabulated in Appendix C. The errors quoted are the quadrature sums of the intrinsic error and the error (1σ) in the zero-point correction. The intrinsic error was calculated using the relation $C / (1 + R)$, where R is defined above and C is an empirically derived constant equal to 8.3 km/s (Pryor, Latham, and Hazen-Liller 1987).

Five members of the sample were too bright ($V < 6$) for the Tillinghast echelle's Reticon to observe. These stars were observed with the Stellar Spectrograph at the McMath Solar Telescope on Kitt Peak. The resolution of these spectra were higher by a factor of ten, so the velocities were measured in the manner described above, but with standard spectra taken with the same instrument.

The projected rotational velocity ($v \sin i$) was estimated by fitting a parabola to the correlation peak and measuring its width (in velocity) at the half maximum level. The base of the peak was not used because its width is more sensitive to the intrinsic width (due to pressure broadening) of the Mg I b lines at small to modest rotational velocities. The calibration of $v \sin i$ to correlation peak width was achieved as follows. Spectra were taken of six stars of various spectral types which were already known to have low rotation rates ($v \sin i < 5$ km/s). These stars were: HD 19445 (F2), HD 112299 (F8), the Sun (G2), HD 102494 (G8), HD 12029 (K2), and HD 115521 (M2). These spectra were synthetically broadened by convolving them with the rotational broadening function given by Gray (1976) and assuming the standard limb-

darkening law with a limb-darkening coefficient of 0.6. Nineteen synthetically-broadened spectra were created for each star, covering rotational velocities from 10 to 100 km/s at 5 km/s intervals, and they were cross-correlated with the standard templates. The correlation peak width was measured, in the same manner as for the program spectra, as a function of $v \sin i$.

The data points of $v \sin i$ versus peak width were fit with a fifth order polynomial using a least-squares technique and are shown in Fig. 3. The F2 calibration is shown in Fig. 3a when cross-correlated against both the A star and solar template. The F8 through K2 calibrations against the solar template are displayed in Fig. 3b, while the M2 calibration against the M star template is in Fig. 3c. As one can see, the calibrations are nearly identical for all stars of types from late F to early K until one reaches high rotational velocities. However, the curves of Fig. 3a indicate that the calibrations are highly dependent on the template which was used. This was not much of a problem, since the correlations used for the M program stars were against the M star template and for the late F through K program stars were against the solar template. But the correlation with the highest R value for the early F stars was sometimes the solar template and sometimes the A star template. In these cases, the calibration used was appropriate to the template used.

The values of $v \sin i$ which were measured are tabulated in Appendix C. The work of Tonry and Davis (1979) suggests that the measurement errors in $v \sin i$ should also be of the form $C / (1 + R)$. Hartmann *et al.* (1986), who provide a more detailed description of this procedure, have shown that the 90 % confidence level error in $v \sin i$ is $\pm v \sin i / (1 + R)$. The errors quoted in Appendix C were calculated using this relation.

Figure 3a. Cross-correlation peak full width at half maximum vs. rotational velocity for synthetically broadened echelle spectra correlated with the standard templates. Both curves represent the F2 rotation standard (HD 19445). The dashed curve results from correlation with the A star template (HD 214994) and the solid curve results from correlation with the Solar template.

Figure 3b. Cross-correlation peak full width at half maximum vs. rotational velocity for synthetically broadened echelle spectra correlated with the standard templates. All curves result from correlation with the Solar template. The dotted curve represents the F8 rotation standard (HD 112299), the solid curve represents the G2 rotation standard (the Sun), the dashed curve represents the G8 rotation standard (HD 102494), and the dot-dashed curve represents the K2 rotation standard (HD 12029).

Figure 3c. Cross-correlation peak full width at half maximum vs. rotational velocity for the synthetically broadened echelle spectrum of the M2 rotation standard (HD 115521) correlated with the M star template (HD 115521).

It is evident from Fig. 3 that this method for measuring $v \sin i$ breaks down at high rotational velocities ($v \sin i > 80$ km/s). At such rapid rates of rotation, a spectrum is so rotationally broadened that it is featureless, save for the shallow depressions which are the remains of the Mg I b lines. The R value of the cross-correlation is too low for the correlation to be meaningful. For these cases, I estimated $v \sin i$ to within 5 km/s by directly comparing the synthetic spectra to the program spectra and selecting the best fit.

One further *caveat* exists regarding the measurement of $v \sin i$ for those stars which exhibit significant variations in their radial velocity (i.e. “astrophysical” binaries). If the star is truly a single-line spectroscopic binary (SB1), then the measured line-broadening does represent the rotational velocity of the primary. But if the star is in fact an unresolved double-line spectroscopic binary (SB2), then the measured line-broadening is partially caused by the orbital motion of the system. In this case, one would expect the amount of line-broadening (i.e. the correlation peak width) to vary with time. Therefore, I only measured $v \sin i$ for those binaries whose correlation peak widths did not change from epoch to epoch.

High resolution spectra were also taken of the H_α and Ca II K line profiles of some members of the sample. The echelle spectrographs at the MMT and Tillinghast reflector were used for this purpose, as well as the MMT Spectrograph with echellette grating (0.9 Å resolution). Only the flare stars (Me and Ke dwarfs) were observed systematically at this setting. All others were observed at random, as time allowed. Appendix D summarizes these data. Either the equivalent width of an emission core is given or its absence is noted.

For the flare stars, integrated line fluxes for the H_α and Ca II K lines were estimated from the echelle spectroscopy in the following manner. The continuum flux value at 5500 Å ($f_{\lambda 5500}$) was determined from the Johnson V magnitude. The ratios of continuum fluxes $f_{\lambda 6600}/f_{\lambda 5500}$ and $f_{\lambda 3900}/f_{\lambda 5500}$ were computed for different spectral types using the M dwarf spectrophotometric standards of O'Connell (1973) and Jacoby *et al.* (1984), as well as the spectroscopic standards of Turnshek *et al.* (1985). The products of these ratios with $f_{\lambda 5500}$ for each star were assigned as the continuum flux values of the spectra near H_α and Ca II K. The line profiles were then integrated over wavelength and, for H_α only, the area under the continuum subtracted off. The integrated flux for Ca II K is measured down to the zero flux level since Giampapa, Worden, and Linsky (1982) showed that the residual photospheric flux in the K line is negligible.

Photometry

The photometry reported in this dissertation was obtained either with the Catalina Photometer at the Steward Observatory 1.5 m telescope on Mt. Lemmon, AZ or with the Automated Filter Photometer (AFP2) at the #2-0.9 m telescope on Kitt Peak. Both filter sets were prescribed by Bessel (1976) with UBV on the Johnson system and RI on the Kron-Cousins system. The transformation coefficients were calculated simultaneously using the inverse matrix method described by Harris, Fitzgerald, and Reed (1981) from observations of photometric standards given by Landolt (1983). The UBVRI photometry for my EMSS stellar subsample is presented in Appendix E.

All stars with photometry were plotted on the UBV diagram in order to check the spectral types which were assigned, distinguish between luminosity classes, and look for interstellar reddening (absorption). The main sequence and giant loci in the UBV diagram, as well as the reddening laws, were taken from Golay (1974). Values of E_{B-V} and A_V were calculated for those stars which did lie along the reddening curve from their spectral type.

Distances to each star were calculated using trigonometric parallaxes when available. If not, photometric parallaxes were calculated using the M_V versus $(V - I)_{KC}$ relation of Reid and Gilmore (1982) for the K and M stars, and the M_V versus $(B - V)$ relation of Gliese (1982) for the F and G stars. Those stars for which we were unable to obtain photometry, or which had photometry contaminated by another star, were assigned an M_V from the spectral type using the values given for standards in Boeshaar (1976) for the M stars and Mikami (1978) for earlier types.

The distances are tabulated in Appendix F, along with a description of which type of parallax was used and all values of E_{B-V} which were calculated. After examining the spread in the M_V versus spectral type and color relations, I estimate the errors in M_V to be 1.0 mag for spectroscopic parallaxes and 0.6 mag for photometric parallaxes. The error in these relations is much larger than the error in M_V introduced by the error in measuring colors or by misclassifying a star by one subtype. Errors in M_V for trigonometric parallaxes are usually on the order of 0.1 mag.

Chapter 3

The Relation Between X-ray Emission and Stellar Rotation

Previous Work

Coronal x-ray emission from late-type stars (i.e. those with outer convective envelopes) is caused by non-radiative heating of the upper layers of a stellar atmosphere. The current view is that this process functions due to the presence of magnetic fields which are generated by a magnetic dynamo. The catalyst for such a dynamo is differential rotation and convective motions. Therefore, the obvious parameter to compare with stellar x-ray luminosity is stellar rotation.

The seminal paper on this topic was written by Pallavicini *et al.* in 1981. In it, the authors considered the correlation between soft x-ray luminosity (L_x) and projected rotational velocity ($v \sin i$) for a sample of 34 late-type (F - M), single stars. The sample was chosen from the Center for Astrophysics stellar survey program and other pointed-observation programs of various guest investigators to the *Einstein* Observatory. Rotational velocities were obtained from the literature. Consequently, this sample was optically selected and biased towards the selection criteria of the various *Einstein* observers and optical spectroscopists whose data were used.

Pallavicini *et al.* came to the following conclusions: 1) L_x did correlate with $v \sin i$ in stars of spectral type later than F7. The best fit to the data was $L_x = 10^{27} (v \sin i)^2$ ergs/s; 2) L_x did not correlate with L_{bol} for these same stars. This result was in contrast to their discovery that $L_x = 10^{-7} L_{bol}$ for a sample of O and B stars which they also analyzed; 3) They found no difference

in x-ray behavior between luminosity classes III, IV, and V among the late-type stars; 4) The early F stars fitted neither correlation. They were overluminous in x-rays when placed on the early-type L_{bol} relation and underluminous in x-rays when placed on the late-type $v \sin i$ relation. Finally, while these authors presented data on single stars only, they used the data of Walter *et al.* (1980) on RS CVn binaries to show that, as a class, the RS CVn binaries fell on their L_x versus $v \sin i$ relation. However, there was no correlation between L_x and $v \sin i$ among the individual binaries.

Other studies of optically selected samples have shown a relation between L_x and rotation in late-type stars, although of somewhat different form. Mangenay and Praderie (1984) found that a power law relation between L_x and an effective Rossby number (i.e. a parameter which combines rotation rate with a parameter which characterizes the convection zone) fit the data well for all spectral types. Marilli and Catalano (1984) claimed that the proper correlation was that L_x was an exponential function of rotation period.

I have decided to explore the relationship between L_x and rotation in late-type stars from a different perspective by using my x-ray selected sample. In this way, I avoid the biases associated with the optically selected samples which were mentioned above. Instead, my sample is biased towards strong coronal activity (i.e. x-ray emission). This approach has not been tried before due to the lack of large, x-ray selected, stellar samples and the enormous amount of ground-based observing time required to properly identify and follow-up serendipitous x-ray detections. Indeed, other studies involving x-ray selected samples of stars have suffered from small-number statistics (cf. Favata *et al.* 1988; Caillault *et al.* 1986). In the present study, this difficulty is overcome

by using what I believe to be the largest and best optically observed, x-ray selected sample of stars to date.

Single Stars

I begin the rotation/x-ray analysis with the apparently single stars. This refers to those members of the sample which showed no evidence for radial velocity variation. In Fig. 4, L_x is plotted against $v \sin i$ for these stars. As was mentioned in the previous section, the resolution of the echelle spectra prevent me from measuring $v \sin i$ accurately below 10 km/s. Consequently, those stars in my EMSS subsample for which $v \sin i < 10$ km/s will be of little use in determining the relation between $v \sin i$ and L_x . However, I plot them in Fig. 4 in one bin at $v \sin i = 5$ km/s to see if they generally have values of L_x less than those stars for which $v \sin i > 10$ km/s.

After eliminating the stars which are dubious x-ray sources (i.e. those stars whose positional error circles contain other possible stellar or extragalactic contributors to the x-ray detection), there are 19 stars in the low-rotation bin which have $L_x > 10^{29}$ ergs/s. This is the x-ray luminosity one would expect a star rotating at $v \sin i = 10$ km/s to have from the Pallavicini *et al.* relation. Half of these stars fit well within the scatter about the Pallavicini *et al.* relation. Of greatest concern are the stars which have $v \sin i < 10$ km/s and $\log L_x > 30.5$ ergs/s. There are no single stars in the sample of comparable x-ray luminosity which have $v \sin i > 10$ km/s. However, one must remember that I have identified the binaries in my sample from radial velocity

Figure 4a. Soft x-ray luminosity vs. projected rotational velocity for all single stars from the EMSS subsample. All stars which have $v \sin i < 10$ km/s are plotted in one bin at $v \sin i = 5$ km/s. Stars of spectral type F0 - F6 are represented as solid dots, while those of spectral type F7 - M5 are represented as solid squares. Also plotted are the late-type stars from Pallavicini *et al.* (1981; F0 - F6 are open dots and F7 - M5 are open squares). The solid line represents the $L_x \propto (v \sin i)^2$ relation of Pallavicini *et al.*

Figure 4b. Soft x-ray luminosity vs. projected rotational velocity for all single stars from the EMSS subsample. All stars which have $v \sin i < 10 \text{ km/s}$ are plotted in one bin at $v \sin i = 5 \text{ km/s}$. Only spectral types F7 - M5 are plotted (solid squares). Also plotted are the late-type stars from Pallavicini *et al.* (1981; open squares). The solid line represents the $L_x \propto (v \sin i)^2$ relation of Pallavicini *et al.*. The dashed line represents the $L_x \propto v \sin i$ relation which was fit to the EMSS data.

variations. Any binary systems whose orbital axes are inclined towards the line of sight would be included in the low-rotation bin in Fig. 4. Since there are identified binaries in my sample which do have such high x-ray luminosities, it is reasonable to assume that the x-ray “bright” stars in the low-rotation bin of Fig. 4 are binaries.

In order to retain a proper sense of scale, I have added the data for the late-type stars which were used by Pallavicini *et al.* to Fig. 4. I plot the data for all single stars of spectral types F0 to M5 (excluding PMS stars) in Fig. 4a, while I exclude the points which represent the early F stars (F0 to F6) from Fig. 4b. These figures show that, while some of the EMSS stars fall along the $L_x \propto (v \sin i)^2$ relation, others fall well below it. In addition, the early F stars from the EMSS behave like those from Pallavicini *et al.*, i.e. they also fall below the $(v \sin i)^2$ relation.

Taking the EMSS data points in Fig. 4b which lie above $v \sin i = 10$ km/s, I calculated two statistical parameters to test the significance of correlation: the linear correlation coefficient (Pearson’s r) and the Spearman rank-order coefficient (r_s), as described by Downie and Heath (1965). The results ($r = 0.497$; $r_s = 0.349$) indicate that the null hypothesis which states that L_x and $v \sin i$ are uncorrelated ($H_0(L_x, v \sin i)$) can be rejected at the 99% and 94% confidence levels, respectively. Assuming that L_x and $v \sin i$ are correlated, I fit a power law relation to the EMSS data using the method of least-squares and taking into account the observational errors in both quantities. The stars which have upper limits on $v \sin i$ were included by assigning values of $v \sin i = 5 \pm 5$ km/s to them. The best fit was:

$$L_x \propto (v \sin i)^{1.05 \pm 0.08}$$

where $\chi^2_\nu = 4.09$. This fit is shown in Fig. 4b.

In an attempt to look for correlations with rotational period, however, I found a quite different result. Using the information in Popper (1980), along with color and absolute magnitude, I estimated the radius of each star. Then, the projected angular rotational velocity, $\Omega \sin i$, was calculated for each star by dividing $v \sin i$ by the radius. A plot of L_x versus $\Omega \sin i$ is shown in Fig. 5. The statistical correlation parameters ($r = 0.109$; $r_s = 0.077$) indicate that $H_0(L_x, \Omega \sin i)$ can only be rejected at the 43% and 31% confidence levels, respectively. In essence, L_x does not correlate with $\Omega \sin i$.

As a check, I also estimated the radius of and calculated $\Omega \sin i$ for each late-type star in the Pallavicini *et al.* sample in the same manner. The statistical correlation parameters of L_x versus $\Omega \sin i$ for the Pallavicini *et al.* sample ($r = 0.465$; $r_s = 0.363$) indicate that $H_0(L_x, \Omega \sin i)$ can be rejected at the 94% and 85% confidence levels, respectively. This confirms that L_x really does correlate with rotation for the stars in the Pallavicini *et al.* sample.

Therefore, the correlation seen between L_x and $v \sin i$ for the stars in my EMSS subsample must, in reality, be a correlation of L_x with radius and not rotation. In order to investigate the physical significance of this correlation, I plot L_x versus radius for all single stars in my EMSS subsample in Fig. 6. The statistical correlation parameters ($r = 0.794$; $r_s = 0.672$) indicate that $H_0(L_x, R)$ can be rejected at the 99.9% confidence level in both cases.

Before deciding whether the observed correlation between L_x and radius in the EMSS late-type stars is real or artificially induced, one must consider the empty regions of Fig. 6. First, there is the lower, right-hand corner which represents stars of large radius (e.g. massive dwarfs and giants) and low x-ray

Figure 5. Soft x-ray luminosity vs. projected angular rotational velocity for those single stars from the EMSS subsample which have $v \sin i > 10$ km/s. Only spectral types F7 - M5 are plotted. These data are statistically uncorrelated.

Figure 6. Soft x-ray luminosity vs. stellar radius for all single stars in the EMSS subsample. The symbols are coded by rotation as follows: stars - $v \sin i > 40$ km/s; crosses - $40 > v \sin i > 10$ km/s; solid dots - $v \sin i < 10$ km/s; open dots - no rotation measurement. The dashed line represents the plausible saturation boundary of $L_x^{(sat)} \propto R^2$.

luminosities. In order to be detected by the EMSS, stars with low L_x must be in the solar neighborhood. However, F and G dwarfs and giants are rare within 25 pc of the Sun. Therefore, the sensitivity limit of the EMSS would prevent the detection of such stars. Second, the upper, left-hand region of Fig. 6 represents stars of small radius (e.g. low-mass dwarfs) and high x-ray luminosities. At such high values of L_x , a star could be detected in the EMSS for hundreds of parsecs from the Sun, a volume of space which contains plenty of low-mass dwarfs (i.e. the low-mass dwarfs are much more numerous per unit volume than the higher mass stars which were detected.) Therefore, it is clear that the upper, left-hand region of Fig. 6 is truly empty, whereas the lower, right hand region may contain points which represent stars beyond the EMSS detection limit.

The points in Fig. 6 have also been coded by rotation. One can see that the slow rotators generally have lower values of L_x than the rapid rotators except for the F stars ($R \sim 10^6$ km), where all rotation rates are mixed vertically in the diagram. This implies that L_x is a function of two parameters: rotation and radius (or mass, color, convection zone depth, etc.). L_x increases with rotation until it reaches a limiting value. The upper limit on L_x is a function of radius, increasing with increasing radius. An x-ray selected sample is better suited than all other types of samples for defining this upper limit. One can not formally fit a boundary to a set of data, but I have drawn a line on Fig. 6 (with a slope of 2) which nicely follows the trend in the data. It is highly suggestive that the upper boundary to the data in Fig. 6 (the saturation luminosity, L_x^{sat} , which is described later in this chapter) may have the following functional form:

$$L_x^{(sat)} \propto R^2 \propto M^2$$

since R is nearly proportional to M along the main sequence.

If all late-type stars could be represented in Fig. 6, the collection of all points would not strongly correlate with radius, unlike the upper limit on L_x . But since the EMSS subsample is x-ray selected, it preferentially detects stars which lie along the upper boundary. Therefore, the correlation seen in Fig. 6 is artificially induced by an observational selection effect. This permits us to understand better how the physics of saturation depends on various stellar parameters.

Binary Stars

The L_x versus $v \sin i$ diagram for those EMSS stars in astrophysical binary systems is shown in Fig. 7a. An examination of this figure reveals the fact that narrow-lined, as well as rotationally broadened, spectra are seen among the binaries. Is this what one would expect from a synchronously rotating system? The primary should rotate with a period equal to the orbital period which, in the case of these binaries, is typically less than 10 days. An angle of inclination effect can not be used to explain the presence of narrow-lined spectra among these binaries since the very radial velocity variations which identify them as binaries were observed.

The detection of these narrow-lined binaries, which account for 30% (14 out of 47) of the binaries in my EMSS subsample, can be explained if the

secondary is a faint Me or Ke dwarf. With a large mass ratio, a synchronous binary system could have a primary with a $v \sin i < 10$ km/s and still have detectable radial velocity variations. Such a system would be non-interacting and, in all probability, the true source of the x-rays would be the Me or Ke dwarf companion. Support for this hypothesis comes from one example among these binaries which, due to its apparent brightness, is already well-observed. The F5 dwarf ω Draconis (1E1737.3+6847) is an SB1 whose radial velocity curve is known ($P = 5.28$ days, $k = 35.4$ km/s; Abt and Levy 1976). A typical mass and radius for an F5 dwarf are $1.3 M_{\odot}$ and $1.2 R_{\odot}$, respectively. Suppose that this F5 dwarf is synchronously orbiting with an M2 dwarf ($0.42 M_{\odot}$). Then, the rotational velocity of the F5 dwarf, derived from the equation: $v_{rot} = \frac{2\pi R}{P}$, should be 11.5 km/s. This result is entirely consistent with the observed $v \sin i < 10$ km/s. The amplitude of the radial velocity variation can be estimated by rewriting Kepler's Third Law in the form: $v_{rel} = \left(\frac{M}{P}\right)^{1/3}$, where M is the total mass of the system in units of $M_{\odot}$, P is the period in units of days, and $v_{rel} = v_{primary}/\mu$ is in units of 213 km/s. The reduced mass, μ , of this system is 0.24. Substituting the values given above into this relation, I calculate $v_{primary}$ (the amplitude of radial velocity variation of the primary) to be 35.2 km/s, which is in excellent agreement the observations. Therefore, it is reasonable to assume that ω Draconis has an M dwarf companion. I further suggest that this is probably also true for the other narrow-lined binaries in my EMSS subsample.

Among the binaries in the subsample which exhibit rotationally broadened line profiles, 34% appear to be of the RS CVn type. W UMa type binaries account for 13%, Me dwarfs for 9%, and Ke dwarfs for another 9%.

There are also two cataclysmic variables and one pre-main sequence star among the binary sample (not shown in Fig. 7a).

For those binaries with measurable rotational velocities, the statistical correlation parameters ($r = -0.023$; $r_s = 0.050$) indicate that $H_o(L_x, v \sin i)$ can only be rejected at the 9% and 19% confidence levels, respectively. X-ray luminosity does not correlate with $v \sin i$. Not even the induced correlation with radius is seen, as it is in the case of the single stars (Fig. 4).

However, L_x does appear to correlate with radius, as shown in Fig. 7b, where L_x is plotted against the radius derived from the primary component. The statistical parameters ($r = 0.317$; $r_s = 0.260$) indicate that $H_o(L_x, R)$ can be rejected at the 98% and 93% confidence levels, respectively. It appears that the upper boundary on L_x for the binaries is also a function of radius (or mass, color, etc.). Unfortunately, the binary star data which is displayed in Fig. 7b spans a smaller range in radius than the single star data in Fig. 6.

Furthermore, no great separation is seen in Fig. 7b between stars of different rotation rates. However, I repeat the important *caveat*, made in Chapter 2, regarding the measurement of $v \sin i$ for the binary stars. One can never be quite sure how much of the observed line broadening is due to the rotation of the primary and how much is due to orbital motion. If the system is a single-line spectroscopic binary, then the observed line broadening will be caused by the rotation of the primary. But if the system is a double-line spectroscopic binary which is spectroscopically blended, then the lines will be further broadened by the system's orbital motion. Consequently, the $v \sin i$ values listed for the binaries may overestimate rotation. In fact, I fail to note v

Figure 7a. Soft x-ray (0.3 - 3.5 keV) luminosity vs. projected rotational velocity for the binaries from the EMSS subsample. This plot includes only stars of spectral type F0 - M5 and excludes pre-main sequence stars. All stars which have $v \sin i < 10$ km/s are plotted in one bin at $\log v \sin i = 0.9$. Upper limits on L_x due to ambiguous detections are indicated by arrows.

Figure 7b. Soft x-ray luminosity vs. stellar radius of the primary for all binaries in the EMSS subsample. The symbols are coded by rotation as follows: stars - $v \sin i > 40$ km/s; crosses - $40 > v \sin i > 10$ km/s; solid dots - $v \sin i < 10$ km/s; open dots - no rotation measurement.

$\sin i$ for those binaries whose cross-correlation peak width (i.e. echelle spectral line broadening) varied from epoch to epoch.

Rotational Saturation

The results presented above for the single stars constitute the best observational evidence yet for rotational saturation in the coronae of late-type stars. Unlike previous samples of stars which have been used to support this idea (e.g. Vilhu and Walter 1987), the EMSS subsample was selected to contain the brightest x-ray sources among all types of stars in a completely unbiased (except, of course, for x-rays) manner.

The concept of rotational saturation in coronal, as well as chromospheric, heating has been suggested by several authors to explain the breakdown of the functional dependence between coronal and chromospheric flux and rotation (or Rossby number) at high rotation rates (Vilhu and Walter 1987; Skumanich 1986; Skumanich and MacGregor 1986; Vilhu 1984). The basic argument involves the limited area of the stellar surface. As more surface field is generated with increasing rotation, a point is eventually reached where the stellar surface is totally covered with active regions. The foot-points of magnetic loops crowd each other out and no new loops can be created. Consequently, non-radiative coronal heating reaches a maximum value, and so does x-ray emission. This would explain the dependence of the upper limit to L_x on radius in Fig. 6. This boundary is scaling with surface area.

Another idea involves magnetic feedbacks in the convection zone (cf. Gilman 1983). As increased angular velocity causes the generation of stronger

magnetic fields, the Lorentz forces which result act to decrease differential rotation and inhibit convection in the zone. This, in turn, will decrease magnetic field strength until the differential rotation increases again. This cyclical process would effectively limit the extent to which a corona could be heated. Such an upper boundary would be a function of convection zone parameters and, hence, mass, color, radius, etc.

Even if a stellar corona could be efficiently heated to infinitely high temperatures, there still exists another upper limit to x-ray emission. If one calculates the emissivity in the 0.3 - 3.5 keV energy band from the thermal bremsstrahlung process for a plasma of ionized hydrogen with a density which is typical of the solar corona (10^6 cm^{-3}) as a function of temperature, one finds that it reaches a maximum at $4 \times 10^7 \text{ K}$. This effect is probably not responsible for saturation since this temperature is somewhat high for a bound corona. By equating the escape velocity of a particle in the solar corona to the thermal velocity of a proton ($\frac{GM_{\odot}}{R_{\odot}} = \frac{kT}{m_p}$), I find that protons will escape the Sun (and other main sequence stars since $M \propto R$) at a temperature of $2.3 \times 10^7 \text{ K}$. So it is unlikely that a stellar corona could reach a temperature of $4 \times 10^7 \text{ K}$ unless the protons are confined by another force (e.g. by magnetic fields) as indeed the electrons must be since the temperature at which they should escape is 12,500 K.

The observational results presented above are, by themselves, insufficient to conclusively prove that stellar coronae saturate at high rotational velocities. Ideally, one would wish to plot L_x versus v_{rot} for each star and to normalize both parameters by the saturation value of that parameter which one would expect given each star's radius (mass). Then, all stars would fall on the same

locus of positive slope, increasing to unity and then flattening out to a slope of zero. Unfortunately, the saturation values of L_x and v_{rot} as a function of stellar radius (mass) are not determined. In Fig 8, I attempt to approximate the plot described above by using both L_x/L_{bol} (Fig. 8a) and x-ray surface flux, F_x (Fig. 8b) as surrogates for $L_x/L_x^{(sat)}$. Both quantities are plotted against an unnormalized $v \sin i$, so I have coded each point by spectral type since one would expect the points which represent stars of different masses to fall along separate loci. The value of L_{bol} used for each star is given in Appendix G. The bolometric corrections were computed from the relations given by Pettersen (1983) for the M dwarfs and Hayes (1978) for all other stars.

In both figures, the distribution of points for all spectral types (except perhaps type M) is quite flat. If rotational saturation of stellar coronae is indeed a real effect, then it appears that x-ray selection has given me a sample which only falls along the flat part of the curve which was described in the last paragraph. However, it is interesting to compare the dispersion of the data points in Fig. 8a and 8b. The values of L_x/L_{bol} spread slightly over 3 orders of magnitude, while the spread in F_x is only 1.5 orders of magnitude. Furthermore, the mean values of L_x/L_{bol} and F_x for each spectral type are given in Table 2. The values in Table 2 range over almost 2 orders of magnitude for L_x/L_{bol} , while the values for F_x are within a factor of 2. This suggests that surface area ($4\pi R^2$) is a better surrogate than L_{bol} for $L_x^{(sat)}$ (if it exists).

I have already characterized the saturation boundary in terms of L_x ($L_x^{(sat)} \propto R^2$). Given this and the preceeding discussion, one would expect $F_x^{(sat)}$ to be constant as a function of stellar radius (mass). In Fig. 9, I plot F_x versus B - V color for both single stars and binaries following Fig. 6

Figure 8a. Fractional x-ray luminosity vs. projected rotational velocity for all single stars from the EMSS subsample (excluding ambiguous detections and PMS). Solid dots represent type M, open dots represent type K, triangles represent type G, and stars represent type F. The dashed lines indicate $\langle L_x/L_{bol} \rangle$ for each spectral type (from Table 2). Note the wider spread in the ordinate compared to Fig. 8b.

Figure 8b. Soft x-ray surface flux vs. projected rotational velocity for all single stars from the EMSS subsample (excluding ambiguous detections and PMS). Solid dots represent type M, open dots represent type K, triangles represent type G, and stars represent type F. The dashed lines indicate $\langle F_x \rangle$ for each spectral type (from Table 2). Note the narrower spread in the ordinate compared to Fig. 8a.

Table 2

Mean Coronal Emission Parameters of Single Stars by Spectral Type

	M	K	G	F
$\langle L_x/L_{bol} \rangle$	1.06×10^{-3}	5.40×10^{-4}	1.37×10^{-4}	3.83×10^{-5}
$\langle F_x \rangle$ (ergs cm ⁻² s ⁻¹)	1.10×10^7	7.31×10^6	9.97×10^6	4.09×10^6

of Vilhu and Walter (1987). I use $B - V$ color as the abscissa of Fig. 9 for ease of comparison to the results of Vilhu and Walter. The dashed lines represent their x-ray upper bound for $0.1 < B - V < 0.6$ and the locus of $F_x/F_{bol} = 10^{-3}$, about which most of their M dwarfs fell. The dotted lines represent the loci of $F_x/F_{bol} = 10^{-2.5}$ and 10^{-2} . The EMSS stars lie below their upper bound for the bluer stars, but my sample contains many more K and M stars which reach fractional x-ray luminosities as high as $10^{-2.5}$.

The upper bound on F_x ($F_x^{(sat)}$) appears to increase steadily with color until one reaches $B - V = 0.6$, then it appears that F_x levels off to a constant value ($\sim 7 \times 10^7$ ergs/s/cm²) at $B - V > 0.6$. This constant value represents the point at which the coronal heating mechanism operates at its greatest efficiency. Since F_x is normalized by surface area, $F_x^{(sat)}$ is not directly determined by the radius (such as $L_x^{(sat)} \propto R^2$). The fundamental question which is answered by deciding whether $F_x^{(sat)}$ is constant or $(F_x/F_{bol})^{(sat)}$ is constant (i.e. $F_x^{(sat)} \propto \sigma T_{eff}^4$) is this. Does stellar x-ray emission at saturated levels depend upon the internal energy source, or is it determined purely by surface area?

The steady decrease in $F_x^{(sat)}$ as a function of increasing stellar mass for $B - V < 0.6$ results from the decrease in convection zone depth. According to the magnetic dynamo scenario, poloidal magnetic field is created from the turbulent twisting of the toroidal field which is buoyantly rising through the convection zone (the α -effect). This poloidal magnetic field reinforces the original fields from which the toroidal magnetic field was first created (the Ω -effect) and feeds the dynamo. If the convection zone depth is too shallow (i.e. convective turnover time is too short), then the toroidal magnetic field will float

Figure 9. Soft x-ray surface flux vs. color for all F0 - M5 stars from the EMSS subsample. Single stars are plotted as solid dots, while binaries are plotted as open dots. The dashed lines represent the upper bound to F_x for $0.1 < B - V < 0.6$ given by Vilhu and Walter (1987) and the locus of constant $F_x/F_{bol} = 10^{-3}$. The dotted lines represent the loci of constant F_x/F_{bol} values of $10^{-2.5}$ and 10^{-2} .

to the stellar surface before the α -effect has had time to operate. Thus, the dynamo mechanism and the associated non-radiative coronal heating process are apparently less efficient. This explains why the F stars are underluminous in x-rays at high rotation rates, as illustrated in Fig. 4a.

As for the binaries, their saturation limit in F_x appears to be similar to that of the single stars. The situation for the binaries is more complicated, however, when one considers that the x-ray emitting region is not just the surface area of the primary, but also that of the secondary and the intervening area as well. A complete analysis of these x-ray selected binaries must await the determination of their periods, when one can then draw more significant astrophysical conclusions.

Summary

I have presented x-ray and rotational data for an x-ray selected, flux limited sample of 128 late-type stars. This is the largest and best optically observed x-ray selected sample to date. For single stars of spectral types F7 - M5, $L_x \propto (v \sin i)^{1.05 \pm 0.08}$ but does not correlate with $\Omega \sin i$. Stars of spectral types F0 - F6 are slightly underluminous in x-rays for this relation. However, L_x does correlate with radius for these stars.

These results appear to contradict the earlier work of Pallavicini *et al.* (1981), but in reality they do not. The Pallavicini *et al.* sample was optically selected and, hence, more representative of stars at all levels of activity. It could well be that $L_x \propto (v \sin i)^2$ for stars which are at levels below saturated

activity. My x-ray selected sample is more representative of the highest levels of x-ray activity, which do appear to saturate. These stars lie along the upper limit on L_x , which is a function of surface area, and thus a strong correlation of L_x with radius is artificially induced. When one normalizes L_x by the surface area (F_x), one finds that $F_x^{(sat)}$ increases with color until $B - V = 0.6$, where it appears to level off at a constant value ($F_x \sim 7 \times 10^7$ ergs $\text{cm}^{-2} \text{s}^{-1}$). Although these results do not conclusively prove that rotational saturation in stellar coronae is a real effect, they do indicate that it is plausible. Furthermore, these data (especially as presented in Fig. 6 and 8) suggest that saturation in L_x is a geometric effect caused by limited surface area. The value of $L_x^{(sat)}$ depends most strongly upon radius, rather than T_{eff} .

The L_x for binaries from this sample correlates with neither $v \sin i$ nor $\Omega \sin i$, yet it does correlate with radius. This behavior is different from that of the single stars because the situation in binary systems is more complicated. One must consider emission from both components and the area in between.

Chapter 4

Stellar X-ray Luminosity Functions

The X-ray Luminosity Function

Since an L_x value was obtained for every member of the sample, as well as the total area of sky covered at various flux sensitivities, one can calculate the x-ray luminosity function for the various classes of stars. I emphasize that the central region of each IPC frame (circle having a 5 arcmin radius around the target object) associated with a pointed observation was excluded from the sky coverage in order to avoid selection biases which are based upon observations made at wavelengths other than x-ray. The method used to calculate the luminosity function for an apparent magnitude limited sample is described by Schmidt (1968). Avni and Bahcall (1980) have considered the application of this technique to the simultaneous analysis of more than one complete sample. Since the flux sensitivities of the IPC frames vary over an order of magnitude, the EMSS can be thought of as a collection of complete samples, each having a different limiting sensitivity. By comparing a star's L_x to the various limiting f_x values on each IPC frame, one can calculate the maximum available volume (V_a) in which the star could still have been detected by the survey. In order to correct for the fact that stars in our Galaxy are spatially distributed in a disk, I define V'_a such that $dV'_a = e^{-z/z_0} dV_a$ where z is the height above the Galactic plane and z_0 is the stellar scale height. The assumed scale heights (Ugoren 1963) were 350 pc for the M and K dwarfs, 340 pc for the G dwarfs, 190 pc for the F dwarfs, 270 pc for the K giants, 400 pc for the G giants, 115

pc for the A stars, and 60 pc for the B stars. Then, each star's contribution to the luminosity function is just $1/V'_a$.

Because my sample is purely x-ray selected, I can legitimately calculate such a function. Although only 74% of the x-ray sources within the area studied have been identified, I am confident that 100% of the stellar sources have been identified for the reasons stated in Chapter 2, Section 2. However, the x-ray selection also limits this function to those stars with large L_x values. In addition, this sample is more sensitive to transient x-ray activity (i.e. detection of stars in flare) than optically selected samples. This could be an important effect for the late K and M dwarfs. A limited number of time-resolved x-ray observations of M dwarf flares indicate that L_x can increase by factors of 3 to as much as 30 over quiescent values (Agrawal *et al.* 1986; Ambruster *et al.* 1984; Haisch 1983). So, in a sense, the derived L_x values for these stars might be treated as maxima. However, I believe this bias to be minimal in light of the fact that the $\log \langle L_x \rangle$ of the EMSS M dwarfs is 29.16, which is only a factor of 2 greater than the $\log \langle L_x \rangle = 28.73$ found for young disk M dwarfs from the optically selected sample by Bookbinder (1985). Furthermore, since flaring occurs quite frequently in young M dwarfs, it might not even be appropriate to speak of a "quiescent" coronal luminosity.

The x-ray (0.3-3.5 keV) luminosity of each star, as well as its contribution to the luminosity function ($1/V'_a$), is listed in Appendix G. The "bright" end of the stellar x-ray luminosity function ($\log L_x > 27.8$ ergs/s) is presented in Table 3 and Fig. 10. The x-ray luminosities are binned into intervals of 0.4 in $\log L_x$ (which corresponds to the size of an optical magnitude) and the stellar space densities are divided into four absolute magnitude (M_V) intervals

which roughly correspond to spectral types M, K, G, and F. Actually, the late F dwarfs (F7 - F9) are grouped with the G dwarfs since these stars are very solar-like in their behavior. The number of stars in each bin is given in parenthesis. Error bars represent the logarithmic weighted Poisson errors. As for the 6 stars with maximum values of L_x , their minimum values of $1/V'_a$ are included since I have no way of dividing L_x among them. As long as both stars in each case are contributing to the x-ray detection, then the points in Fig. 10a represent lower limits. There are no stars of spectral type later than M5 represented in this distribution.

To test the uniformity of the sample further, I have calculated $\langle V'_e/V'_a \rangle$ as defined by Avni and Bahcall (1980). This is similar to the V/V_{max} test of Schmidt (1968) except that all survey fields are used in the calculation instead of just the field of detection. The 6 M dwarfs for which only maximum values of f_x exist due to ambiguous detections are excluded from this analysis. Overestimation of f_x (and, hence, L_x) causes an underestimation of the value of V'_e/V'_a for a given star. For a spatially uniform sample of 122 stars, one would expect $\langle V'_e/V'_a \rangle = 0.5 \pm 0.026$. I calculate $\langle V'_e/V'_a \rangle = 0.488$. This indicates that the combination of assumptions made regarding scale height, uniformity, and limiting flux are consistent and that my estimate of V_a is reasonable.

The values of $\langle V'_e/V'_a \rangle$ for each spectral type (excluding giants) are listed in Table 4. The sample remains uniform for the scale heights assumed within each spectral class, although the test just barely succeeds for the K dwarfs. There are not enough detections to make this statement for the giants. I also note that $\langle V_e/V_a \rangle = \langle V'_e/V'_a \rangle$ for the M and K dwarf samples, which is not surprising since all of the M and most of the K dwarfs are within 200 pc of

Table 3

The Stellar X-ray Luminosity Function

$\log L_x$	Φ ($10^{-3} \text{ pc}^{-3} \text{ mag}^{-1}$)			
	M	K	G	F
	Single			
28.0	21.82 (5)	...	4.810 (1)	...
28.4	4.034 (5)	.7900 (1)	1.187 (2)	...
28.8	1.652 (6)	1.328 (5)	.7890 (3)	...
29.2	.4249 (5)	.1829 (3)	.5126 (7)	.2549 (3)
29.6	.0515 (4)	.0113 (1)	.0852 (4)	.0931 (4)
30.0	.0080 (2)	.0113 (3)	.0141 (3)	.0255 (4)
30.4	...	...	...	...
30.8	...	...	.0025 (5)	...
	Binary			
28.0	...	...	...	...
28.4	...	2.148 (2)	...	...
28.8	...	...	...	.2990 (2)
29.2	.1511 (2)	.1180 (1)	.1030 (1)	.2937 (3)
29.6	.0544 (2)	.0446 (3)	.1399 (6)	.0226 (2)
30.0	...	.0172 (4)	.0325 (5)	.0108 (1)
30.4	...	.0016 (1)	.0092 (4)	.0015 (1)
30.8	...	.0005 (1)	...	...

Table 4

Test for Uniformity

	M	K	G	F
No. of Stars	25	26	28	35
Confidence Interval	.058	.057	.055	.049
$\langle V'_c/V'_a \rangle$	.517	.445	.491	.496

Figure 10a. X-ray luminosity function of late-type dwarfs. Solid dots represent type M, open dots represent type K, triangles represent type G, and stars represent type F. Error bars represent the logarithmic weighted Poisson errors.

Figure 10b. X-ray luminosity function of late-type dwarfs expressed in terms of fraction of all dwarfs of that spectral type. Total numbers of dwarfs come from the optical luminosity function of Wielen, Jahreiß, and Kruger (1983). Solid dots represent type M, open dots represent type K, triangles represent type G, and stars represent type F. Error bars represent the logarithmic weighted Poisson errors.

the Sun. Compared to a disk scale height of 350 pc, the stars within this volume should appear to be distributed isotropically.

The following observations can be made about Fig. 10. The slope of the bright end of the stellar x-ray luminosity function is pretty much the same for spectral types G through M. Using a weighted, least-squares fit, I find that the slopes of the M- and K-dwarf functions and the G-dwarf function greater than $L_x = 10^{29}$ ergs/s are identical within $\pm 1\sigma$. The mean value of the slope is -1.51 ± 0.13 . The G - M dwarf luminosity functions in Fig. 10a have identical slopes within the errors, only each one is shifted to the right (higher L_x) as an increasing function of mass (L_{bol}). The G dwarfs dominate in the x-ray bright bins since they are capable of greater x-ray luminosities than the later-type dwarfs (see Chapter 3).

The obvious question to ask is why $\Phi \propto L_x^{-1.5}$ at the x-ray bright end of the luminosity function for all dwarfs between F7 and M5. Remember that Φ represents the number density of stars per x-ray magnitude. The functional dependence on L_x for the number density of stars per incremental x-ray luminosity

$$n(L_x)dL_x \propto L_x^{-2.5}dL_x$$

Could rotational saturation of the corona be responsible? Or are we seeing the effects of time evolution in L_x ? The current number density of dwarfs as a function of mass:

$$n(M, t_o) = \int_{\max(0, t_o - \tau_{MS}(M))}^{t_o} C(M, t) dt$$

where t_o is the age of the Galactic disk, $\tau_{MS}(M)$ is the main sequence lifetime of a star of mass M , and $C(M, t)$ is the stellar creation function. In analyses

like this, it is customary (cf. Scalo 1986) to assume that $C(M, t)$ can be separated into independent functions of mass and time, $C(M, t) = \Psi(M)B(t)$, where $\Psi(M)$ is the time-invariant initial mass function and $B(t)$ is the stellar birthrate function. For the initial mass function, I assume the Salpeter relation $\Psi(M) \propto M^{-2.35}$ (Salpeter 1955). Twarog (1980) has shown that the local stellar birthrate function is essentially constant over the past 4×10^9 yrs. Since the x-ray bright stars in my sample are all younger than this, I will take $B(t)$ to be constant. Therefore, after performing the integration above, one finds that:

$$n(M, t_o)dM \propto M^{-2.35} \min(t_o, \tau_{MS}(M))dM$$

In fact, if we assume a constant $B(t)$, then $n(M, t_o)$ is independent of stellar age (τ). At any given mass on the main sequence, the number density of stars at any particular age is equal to the number density of stars at any other particular age. Thus, for a given mass, the number density of stars as a function of L_x for those values of $L_x < L_x^{(sat)}$ (i.e. for those stars which are older than $\tau_{sat}(M)$, the age at which the Ω of a star of mass M has sufficiently decreased so that its corona is no longer saturated) is determined by the functional dependence of L_x on τ . Simon, Herbig, and Boesgaard (1985) have presented evidence that x-ray flux does decrease with stellar age.

On the other hand, the number density of stars of mass M which are coronally saturated ($\tau < \tau_{sat}(M)$) and, hence, have only one value of L_x is

$$n_{sat}(M, t_o) = \frac{\tau_{sat}(M)}{\min(t_o, \tau_{MS}(M))} n(M, t_o)$$

Therefore, the behavior of $\int n(M, t_o)dM$ as a function of L_x can be described as a superposition of the saturated and unsaturated values of $n(M, t_o)$ for all

masses. In Chapter 3, I showed that $L_x^{(sat)} \propto M^2$. Assuming the values of $n_{sat}(M, t_o)$ will dominate the n versus L_x relation, one could try expressing $n_{sat}(M, t_o)$ in terms of L_x :

$$n_{sat}(M, t_o) dM \propto \tau_{sat}(M) M^{-2.35} dM \propto L_x^{-\frac{\alpha}{2}} L_x^{-1.18} L_x^{-0.5} dL_x$$

Unfortunately, due to the lack of a well-calibrated L_x versus τ relation for different masses of stars (to be discussed in the next section), the exact dependence of $\tau_{sat}(M)$ on M is unknown. For the present calculation, I have assumed a power law for $\tau_{sat}(M) \propto M^{-\alpha}$. Thus, the equation above reduces to:

$$n_{sat}(L_x) dL_x \propto L_x^{-1.68 - \frac{\alpha}{2}} dL_x$$

This estimate matches the empirical result if $\alpha = 1.64$. However, this prediction for the value of α can not be observationally tested yet. Suffice it to say that the slopes of the G- through M-dwarf functions in Fig. 10 are probably induced by saturation, since it is plausible to assume that, at a given value of L_x , the number density of lower-mass, saturated dwarfs will be greater than the number density of higher-mass, unsaturated dwarfs.

The F-dwarf luminosity function (types F0 - F6) appears quite different from the other functions in Fig. 10. At the bright end, it falls below the G- and K-dwarf functions, while at the faint end, it turns over at $L_x \sim 10^{29}$ ergs/s. This first observation is consonant with the empirical result that early F dwarfs are underluminous in x-rays compared to later-type dwarfs at rapid rotation rates (i.e. young ages; Schmitt *et al.* 1985b; Chapter 4 of this work). I suggest that the turnover seen at the faint end is a manifestation of the relatively short (compared to later-type dwarfs) main sequence lifetimes of early F dwarfs.

Since levels of x-ray emission (as well as chromospheric activity) decrease with age in late type dwarfs (Simon, Herbig, and Boesgaard 1985; Giampapa 1988), the bins of low L_x in Fig. 10a represent older stars than those of higher L_x within the same spectral type. Therefore, one would expect the number of dwarfs at low values of L_x to decrease once one reaches the age at which that type of dwarf evolves off of the main sequence. Considering values of $\log L_x > 27.8$ (the effective sensitivity limit of the EMSS), only the early F dwarfs reach this point among late type dwarfs.

In order to verify the plausibility of this last statement, I present the following order of magnitude calculation. According to Iben (1967), the main sequence lifetimes for a typical early F dwarf ($1.5 M_\odot$) and solar-type dwarf ($1 M_\odot$) are 10^9 and 7×10^9 yrs, respectively. Giampapa (1988; Fig. 4) presents a compilation of available x-ray surface flux (F_x) versus age data for solar-type stars in graphic form. The amount of data is too small to derive a formal relation. Therefore, I make crude estimates of F_x directly from the figure. At 10^9 yrs, $\log F_x \approx 5.6$ ergs/s/cm², while at 7×10^9 yrs, $\log F_x \approx 4.2$ ergs/s/cm². Since even less information is available for the early F dwarfs, I must use the solar-type relation. After multiplying the surface fluxes by the surface areas of a typical early F dwarf ($1.6 R_\odot$) and solar-type star ($1 R_\odot$), I get $\log L_x \sim 28.8$ ergs/s for the early F dwarfs and $\log L_x \sim 27.0$ ergs/s for Solar-type stars as the x-ray luminosities where one would expect the space density to drop due to stellar evolution.

New Method for Measuring the Recent Stellar Birthrate

The stellar x-ray luminosity function, as presented above, can yield information on the recent stellar birthrate, if one knew for certain the relation between L_x and age. The direct measurement of stellar age for field stars is quite difficult. For M stars, it is almost impossible. But for solar-type stars, one can observe the Li I absorption line at 6707 Å. The strength of this line can be used to calculate Li I abundance (Duncan 1981). Since Li I is mixed downward in the stellar atmosphere and destroyed at higher temperatures, thus decreasing with stellar age, the line strength correlates directly with age at a given T_{eff} and $\log g$. Simon, Herbig, and Boesgaard (1985) used Li I measurements in their study of time evolution in chromospheric line fluxes which was cited above.

While considering the time evolution of coronal flux, it is best to use x-ray surface flux (F_x) in order to reduce the scatter introduced by the dependence of L_x on mass (surface area). If the F_x versus age relation were well calibrated, one could use F_x as an age indicator, and assign ages to all stars (assuming each one's radius) in the luminosity function. Then, the space density information can be rebinned by age, thus yielding the age distribution of late-type main sequence stars. This function would be valuable in determining the rate of star formation over the past billion years.

I have attempted this exercise for the solar-type dwarfs using the meager F_x versus age information given in Giampapa (1988). The results are presented in Fig. 11 in terms of the fraction of all solar-type dwarfs ($3.5 < M_v < 5.5$) as a function of age. The crosses in Fig. 11 represent what one would expect

if the local stellar birthrate were constant, assuming a main sequence lifetime of 7×10^9 yrs (Iben 1967). These results would indicate a decreasing stellar birthrate with time over the last billion years, which is in direct conflict with Twarog (1980). However, the data points in Fig. 11 should not be trusted, since the F_x versus age relation is extremely uncertain.

In order to make this method useful, we need a well calibrated relation between F_x and age for late-type stars. I propose two plans of attack to obtain this information. One is to take a well-defined set of stellar x-ray observations (namely, this sample) and obtain high-resolution Li I profiles of each star in order to measure its age. The other plan is to take a well-defined sample of stars whose ages are already known from Li I line profiles (e.g. the sample of Duncan 1981) and measuring F_x for each one by searching for them in the x-ray all-sky survey which will be performed by ROSAT, the next x-ray telescope which is due to launch in 1989.

Stellar age distributions constructed in this way will be superior to previous determinations since we are using F_x as the age indicator and an x-ray survey for which detection sensitivity is known for each area of the sky observed. Such a similar survey does not exist for the Li I photospheric line or any of the chromospheric lines.

Figure 11. The stellar age function for solar-type stars ($3.5 < M_v < 5.5$). The crosses represent what the age function should look like if the star formation is constant, assuming a main sequence lifetime of 7×10^9 yrs. The arrow and leftmost cross indicate the fraction of all stars younger than 2×10^8 yrs, the age below which saturation makes it impossible to assign ages from x-ray flux.

Binaries

The x-ray luminosity functions for single stars and binaries are compared in Fig. 12. Once again, the functions are almost identical except at the x-ray faint end. This divergence at $\log L_x < 29$ ergs/s is an artifact of the curious paucity of binaries among the EMSS M-dwarf detections, the details of which are discussed in Chapter 5. But as far as the K through F dwarfs are concerned, it appears that binaries and single stars are evenly distributed at high x-ray luminosities throughout this region of the Galaxy. This result is quite remarkable and unexpected. I am presently unable to decide whether this result is coincidental or not and, if not, to determine the reason for it.

Of particular interest are the “active” binaries of the RS CVn and W UMa types. RS CVn binaries are detached, synchronously rotating systems which were defined by Hall (1976). There are three basic requirements for membership in the class: 1) the orbital periods are between 1 and 14 days; 2) the hotter component has a spectral type of F or G V - IV, while the cooler component (not always seen) is usually K0 IV; 3) enhanced Ca II H & K emission is observed. The W UMa stars are F and G type, contact binaries whose periods are less than 1 day (again see Hall 1976). Light curves of both types of binary indicate that their stellar surfaces are covered with starspots (analogous to sunspots).

My EMSS subsample contained 2 previously catalogued RS CVn binaries (HD 108102 and HD 136905) and 1 previously known W UMa binary (AH Vir). I have identified 14 new candidates for the RS CVn and 5 new candidates for the W UMa classes from my EMSS subsample. The RS CVn

Figure 12. X-ray luminosity function for F0 - M5 dwarfs as a function of duplicity. The solid dots indicate single stars while the open dots indicate binaries. Error bars represent the logarithmic weighted Poisson error.

binary candidates were selected on the basis of variable radial velocities, rotationally broadened line profiles, spectral type (F or G V - IV), and Ca II H & K emission. The selection of the W UMa candidates was less straightforward. With periods of less than a day, W UMa binaries exhibit rotational velocities ~ 100 km/s. At these velocities, at echelle resolution, the photospheric lines at $5200 \text{ \AA}$ disappear (cf. Chapter 2). Therefore, I can not measure radial velocities for these stars and, hence, do not know if they are velocity variables. I have assumed that all F and G dwarfs in my sample which have $v \sin i \sim 100$ km/s (i.e. spectroscopically similar to AH Vir) are W UMa candidates. I use the term "candidate" since light curves should be obtained for each star before membership in either class can be confirmed.

I mention these two classes of binaries in order to make an interesting point. Pointed surveys with the *Einstein* Observatory of nearly all catalogued RS CVn (Walter and Bowyer 1981) and W UMa (Cruddace and Dupree 1982) binaries have shown that all of these objects are strong x-ray emitters ($L_x > 10^{29}$ ergs/s). Since these luminosities are well above the sensitivity limit of the EMSS, one can reasonably assume that the RS CVn and W UMa binaries detected in my sample are representative of all such binaries. Therefore, an x-ray survey (such as mine) could be used to calculate the total space density of RS CVn and W UMa binaries in much the same way as photographic color surveys have been used to calculate the total space densities of white dwarfs or M dwarfs.

The space densities of RS CVn and W UMa binaries would provide important constraints on theories of stellar evolution. Are RS CVn binaries the progenitors of cataclysmic variables? Which main sequence stars evolve

through the RS CVn or W UMa phase? Do W UMa binaries evolve into FK Com stars? (For more on this question, see Chapter 6.) Comparison to the space densities of other classes of stars would test theoretical calculations of evolutionary timescales. Unfortunately, as I mentioned in the introduction, this is a topic which will not be thoroughly treated in this dissertation. I discuss it here as future work, since the RS CVn and W UMa candidates must be followed-up to confirm their identities. However, assuming these candidates are *bona fide*, the local space densities for RS CVn and W UMa binaries would be $4.50 (\pm 1.13) \times 10^{-4} \text{ pc}^{-3}$ and $8.15 (\pm 3.33) \times 10^{-5} \text{ pc}^{-3}$, respectively. To my knowledge, this is the first such estimate made for RS CVn binaries. Duerbeck (1984) has estimated a space density of $3.21 (\pm .21) \times 10^{-5} \text{ pc}^{-3}$ for all W UMa binaries, while van 't Veer (1975) obtained $1.1 \times 10^{-4} \text{ pc}^{-3}$. My estimate is of the same order of magnitude.

Comparison with Optically Selected Samples

It is useful to compare these results with the known distribution of stars in the solar neighborhood from optical data. A summary of all such work was recently given by Scalo (1986). Because of its reliance on trigonometric parallaxes, sample size, and completeness for $4 < M_V < 10$, I use the luminosity function of Wielen *et al.* (1983). This luminosity function agrees well with the function adopted by Scalo (1986) for his study of the initial mass function.

The data of Fig. 10a are replotted in Fig. 10b with the values of all points of each spectral type divided by the local space density of all dwarfs of that spectral type. This operation separates the curves of Fig. 10a since the

local space densities decrease with increasing mass (earlier type). At a given x-ray luminosity, there are a greater fraction of early type dwarfs than later types. But this statement can not be made for a given age since all dwarfs of various masses at a given x-ray luminosity are not coeval.

This computation of the ratio of the number of x-ray bright dwarfs to all dwarfs of a given spectral type is necessary in order to compare my x-ray luminosity functions to those calculated from optically selected, volume limited, stellar samples. These functions are given by Schmitt *et al.* (1985b) for the F0 - F6 dwarfs, by Maggio *et al.* (1987) for the late F and G dwarfs, and by Bookbinder (1985) for the K and M dwarfs. Since their samples were not x-ray selected and flux limited, these authors could not use the $1/V_d'$ technique. Instead, they employed a non-parametric, statistical technique known as "survival analysis" (Avni *et al.* 1980) which uses a maximum likelihood algorithm to determine how representative their stellar samples, both detections and upper limits, are of the stellar x-ray parent distribution. As a result, they can only estimate the fraction of an entire population at a given x-ray luminosity (not space densities), but for a wider range of x-ray luminosities than can be inferred from x-ray selected samples.

The integral x-ray luminosity functions derived from optical and x-ray selection are compared in Fig. 13. The number of x-ray bright G dwarfs have been severely underestimated by the optically selected samples. The number of x-ray bright F dwarfs have been only slightly overestimated. Yet both sets of functions dovetail nicely at the point where the x-ray selected function stops. The K-dwarf functions agree at the x-ray bright end, but x-ray selection indicates a greater number of stars at lower x-ray luminosities.

Figure 13a. Integral x-ray luminosity function for single F0 - F6 dwarfs expressed as the fraction of all F dwarfs. The solid histogram was calculated using the x-ray selected sample from the EMSS, while the dotted histogram was calculated using the optically selected sample of Schmitt *et al.* (1985b).

Figure 13b. Integral x-ray luminosity function for single F7 - G8 dwarfs expressed as the fraction of all G dwarfs. The solid histogram was calculated using the x-ray selected sample from the EMSS, while the dotted histogram was calculated using the optically selected sample of Maggio *et al.* (1987).

Figure 13c. Integral x-ray luminosity function for single K dwarfs expressed as the fraction of all K dwarfs. The solid histogram was calculated using the x-ray selected sample from the EMSS, while the dotted histogram was calculated using the optically selected sample of Bookbinder (1985).

Figure 13d. Integral x-ray luminosity function for single M dwarfs expressed as the fraction of all M dwarfs. The solid histogram was calculated using the x-ray selected sample from the EMSS, while the dotted histogram was calculated using the optically selected sample of Bookbinder (1985).

The explanation for the behavior of the G- and F-dwarf functions is simple. The volume limited samples did not cover a great enough volume of space to include the very x-ray brightest G and F dwarfs. Although this statement is not true for the K dwarfs, it appears that their overall x-ray activity levels have been underestimated by just studying the K dwarfs within 25 pc of the Sun (the volume limit of the Bookbinder sample).

The Uncounted M Dwarfs

The x-ray luminosity functions for the M dwarfs present a problem. The function derived from optical selection predicts a far greater fraction of M dwarfs at values of $\log L_x > 28.2$ ergs/s. This function is taken from Bookbinder's (1985) far (25 pc) sample. The luminosity function derived from his near (10 pc) sample is more in line with the EMSS function. One major difference between the x-ray data of Bookbinder's near and far samples is that the far sample contains more upper limits at x-ray luminosities greater than 10^{28} ergs/s. I suggest that the number of x-ray bright M dwarfs in Bookbinder's far sample is overestimated due to this fact.

This is not to say that there are not problems with the EMSS luminosity function. The M-dwarf x-ray function is normalized to a total function which the authors (Wielen *et al.* 1983) estimate is incomplete beyond 10 pc at $M_v > 12$. Indeed, the whole question of luminosity function biases on the lower main sequence is summarized nicely by Reid (1987). This problem will be treated more fully in Chapter 5, a chapter devoted entirely to the M dwarfs. However, while I am still discussing the luminosity function data, I wish to merely point

out the following. The data of Wielen *et al.*, which come from the Gliese Catalogue, indicate that there are 12.7 stars per thousand pc^{-3} in the interval $14.5 < M_V < 15.5$. The local space density of x-ray bright ($\log L_x > 27.8$ ergs/s) stars for $14.5 < M_V < 15$ is 14.5 stars per thousand pc^{-3} .

My EMSS subsample contains 8 M dwarfs which appear to be within 25 pc of the Sun from photometric and spectroscopic parallaxes and yet are not in any of the proper motion catalogues or the Gliese catalogue. X-ray bright M dwarfs are expected to be young and should therefore have low tangential velocities. Therefore, it is not surprising that they would be missed in a proper motion survey. The EMSS has shown that x-ray surveys provide an efficient way to actually locate these young, low-mass dwarfs which are missing from the nearby-star catalogues. X-ray and proper motion surveys complement each other since they preferentially select young and old stars, respectively.

The Giants

Since there are only 6 giants in my EMSS subsample, I will not attempt to construct an x-ray luminosity function for them or say anything useful about their distribution. I wish only to make one point. The latest giant detected is of spectral type K0. A recent summary was given by Haisch (1988) on the present status of the Linsky-Haisch dividing line (see Chapter 1) in the H-R Diagram. In it, he states that x-rays have still not yet been detected from a single red giant later than type K2. My x-ray selected sample provides no evidence to the contrary.

Chapter 5

The M Dwarfs

Coronal and chromospheric activity in M dwarfs has been an area of active research in recent years (cf. Linsky 1980; Rosner, Golub, and Vaiana 1985; Stauffer and Hartmann 1986; Liebert and Probst 1987; Giampapa 1987). More sensitive detectors on large telescopes have provided much new data on these relatively faint stars. M dwarfs can emit a greater percentage of their bolometric flux (as much as 1%) at high energy wavelengths (soft x-ray and extreme UV) than do stars of greater mass. Active M dwarfs make a significant contribution to the diffuse soft x-ray background (Rosner *et al.* 1981; Bookbinder 1985) and may contribute significantly to the energy budget of the interstellar medium (Coleman and Worden 1976). As for more massive, main sequence stars, there is also evidence that this activity declines with age (Micela *et al.* 1988; Skumanich and MacGregor 1986; Bookbinder 1985; Skumanich 1972). This is not so apparent for the M dwarfs since, compared to earlier types, a greater percentage of them show evidence for chromospheric activity. Nonetheless, there is evidence that the level of coronal activity, as measured by the x-ray luminosity (L_x), declines markedly toward the lowest mass, dwarf M stars (Golub 1983; Ruciński 1984; Bookbinder 1985). By contrast, L_x maintains at least the same fraction of the bolometric luminosity (L_{bol}), and a relatively greater fraction of the non-photospheric energy release seems to occur in the coronae of M dwarfs, rather than in the chromospheres. The differences in the coronal and chromospheric properties of M dwarfs spanning a range in fractional depth of their convection zones provides an empirical test of the general applicability of dynamo models developed in a solar context.

Most of our knowledge of the x-ray properties of M dwarfs – as for virtually all other classes of stars – comes from observations with the *Einstein* Observatory. Prior statistical work in this field, however, has involved samples of previously catalogued stars which were either pointed targets or serendipitous detections (Pallavicini *et al.* 1981; Bookbinder 1985; Johnson 1986; Agrawal *et al.* 1986). Bookbinder's (1985) thesis sample was a comprehensive collection of observations of some 21% of the K and M dwarfs in the Woolley *et al.* (1970) catalogue of known stars within 25 pc of the Sun. This set was as close to a volume-limited sample as was readily available at that time. *

However, there are two obvious biases present in a sample of previously-discovered M dwarfs. First, some of these stars were initially identified in proper motion surveys. Thus, the stars with higher tangential velocities will be represented in higher percentages than the low velocity stars in the Woolley (or Gliese) Catalogue within a given absolute magnitude range. Secondly, the stars of least luminosity will have much lower fractional completeness because they are also apparently faint. This second effect is particularly severe for surveys of limited solid angles of the sky, using colors or objective prism spectra. In particular, the fraction of stars with $M_V > +15$ is much higher in the known sample within 5 pc of the Sun than it is in the samples out to 20-25 pc (Upgren and Armandroff 1981; Wielen, Jahreiß, and Kruger 1983).

* Note that the supplement to an alternative catalogue of Gliese and Jahreiß(1979) contains many new listings and updates earlier discoveries of known stars within about 20 pc ($\pi > 0.045$ arcsec) of the Sun. Moreover, a substantial number of late M dwarfs have been identified subsequently to both catalogues.

The potential selection against low velocity stars in the solar neighborhood is much more difficult to quantify.

Bookbinder (1985) recognized that his M dwarf sample might suffer from the requirement that both the pointed targets and serendipitous detections had to appear in the catalogue of previously-known stars. He attempted to allow for the discrimination against lower luminosity stars in the sample in two significant ways. First, he utilized a subset of the Woolley Catalogue, consisting of stars within 10 pc of the Sun. This he argued to be relatively complete even down to the faintest M dwarfs. Secondly, he presented arguments based on statistical modelling of the $\log N - \log S$ distributions that there was no need to include a substantial (undiscovered) population of x-ray bright, late M dwarfs as a contributor to the mix of *Einstein* Observatory serendipitous sources. Bookbinder concluded that the deficiency of bright x-ray emitting stars of late M spectral type in his sample was a real effect.

Given the importance of these results, further examination utilizing a new sample free from the uncertainties associated with optical selection becomes appropriate. My x-ray selected sample was investigated spectroscopically and photometrically to determine if a significant number of late M dwarfs were serendipitously discovered. Note that only rather crude spectral types are available for the M dwarfs identified as counterparts to serendipitous x-ray sources in the previously published MSS (Gioia *et al.* 1984; Stocke *et al.* 1983; Maccacaro *et al.* 1982) and other parallel investigations (Caillault *et al.* 1986).

Secondly, I obtained detailed observations from which the basic stellar parameters of the M dwarfs in an x-ray selected sample, including absolute magnitude, rotation rate, kinematic class, levels of chromospheric activity, and

radial velocity variations associated with a spectroscopic binary system can be inferred. It was important to determine if the basic properties of an x-ray selected sample of M dwarfs differed from the optical samples, and how these might be related to the level of coronal energy release. A flux-limited, x-ray selected sample with the proper optical follow-up observations allows a more complete, and slightly more rigorous, analysis of the x-ray properties of these stars, but only for the x-ray “bright” M dwarfs.

Estimates of Mean Stellar Age

The mean age of the EMSS M dwarf sample could be estimated from kinematics if I were able to compute space motions for all members. This is impossible since only 5 members of the sample appear in the proper motion catalogues. I calculate their space motions to be young disk using the criteria of Eggen (1969) and from the fact that 4 out of 5 have $|W| < 15$ km/sec. Young *et al.* (1987) point out in a recent paper that at least half of the Me dwarfs are observed to be in astrophysical binaries because the presence of a companion perpetuates Me activity for a longer period than would be observed in single Me dwarfs. Therefore, it is reasonable to assume that an apparently single Me dwarf should on average belong to a younger population. Unfortunately, since the apparently faint M dwarfs require long integration times to obtain useful echelle spectra, I do not have sufficient coverage to determine the binary frequency for the entire sample. Of the 20 stars with such coverage, only 4 are binaries. This suggests that the strong x-ray emission may not be attributed

to close binary dynamical interaction for half of the sample, implying that they are young disk stars.

I note that the fraction of astrophysical binaries discovered in my x-ray selected sample is significantly lower than that in the optically selected sample of Young *et al.* (1987). If this result is real, it would imply that single Me dwarfs have, on average, higher x-ray luminosities than those in astrophysical binary systems. Indeed, this is what one would expect if the binary Me dwarfs are a statistically older group than the single Me dwarfs, given that L_x decreases with age. However, I must caution that the binarity status of a third of the sample is still in question. With such a small sample, the binaries could still be “hiding” in this third which is composed of mostly the lowest mass members of the sample.

It is far from certain what age is implied by the kinematical classification “young disk”. While Eggen (1969) states that the young disk represents stars of age $\tau \leq 5 \times 10^8$ yrs, the calibrations of Jahreiß and Wielen (1983) indicate that stars which display young disk kinematics have ages $\tau \leq 3 \times 10^9$ yrs. Most authors avoid relating kinematic data directly to stellar age, opting instead to use some indirect indicator of age, such as Ca II H & K emission strength. This is due to the fact that, besides the Sun, no age calibrators exist beyond 10^9 yrs. Therefore, when considering young disk objects, one could be dealing with ages up to several billion years.

Finally, studies of rotational velocities for low mass stars in the Hyades (Stauffer, Hartmann, and Latham 1987) and the Pleiades (Stauffer *et al.* 1984) reveal that M dwarfs in the Pleiades ($\tau \sim 7 \times 10^7$ yrs) rotate with $v \sin i \sim 50$ km/s, while the $v \sin i$ measurements of M dwarfs in the Hyades ($\tau \sim 6 \times 10^8$

yrs) fall between 10 and 20 km/s. About half of my sample falls above the detection limit of 10 km/s. The largest $v \sin i$ measured is 34 km/s, while most fall between 20 and 30 km/s. This indicates that the M dwarfs detected in the EMSS range in age from somewhat younger than the Hyades to arbitrarily older than Hyades (i.e. $\tau \leq 1-3 \times 10^9$ yrs).

The kinematical data for the EMSS M dwarfs are sketchy and the calibrations of kinematics and rotational velocity with age are not well established for ages $\geq 10^9$ yrs. The luminosity function data (Chapter 4) indicate specifically that 0.42 ± 0.16 of all local M0-M5 dwarfs have high ($> 10^{27.8}$ ergs/s) x-ray luminosities. Whether this also means that this same fraction of all local M dwarfs were formed in the last 10^9 yrs or the last 3×10^9 yrs can not be determined for the reasons given above. Of particular concern is that, for half of the M dwarf sample, $v \sin i < 10$ km/s (and, presumably, $v_{rot} > 5$ km/s; Bopp and Fekel 1977). Four of the five stars for which we were able to calculate U, V, and W fall into this category, which shows that the slow rotators can have young disk kinematics. These slow rotators are older than the Hyades M dwarfs, but the upper limit to their age is, as discussed above, uncertain.

In a recent series of papers, Eggen (1985 and references therein) has argued that a significant fraction of stars in the solar neighborhood (15% of M dwarfs) may belong to the Hyades supercluster. It is well known that the Galactic disk is inhomogeneous. Should the Sun, at the present epoch, be travelling through a region affected by unusually high, recent star formation, then the local luminosity function would be dominated by young moving groups, such as the Hyades supercluster, which could account for a large fraction of

young, x-ray bright M dwarfs should the age of the entire EMSS M dwarf subsample be $\leq 10^9$ yrs. However, in the next section, I suggest a more plausible explanation for the high fraction of x-ray bright M dwarfs.

Coronal Flux from Early M Dwarfs

L_x appears to be a function of both mass and stellar rotation (age) for the M dwarfs (Golub 1983; Pallavicini *et al.* 1981; Micela *et al.* 1988). Ruciński (1984) pointed out that, while L_x does decrease with later spectral type among detected M dwarfs, L_x/L_{bol} does not. That is to say, the mean L_x/L_{bol} value remains approximately constant as a function of spectral type (mass). The mean L_x/L_{bol} is essentially constant with mass for early M dwarfs, but the wide dispersion at given mass is due to the dependence on another parameter. My data confirm that this parameter is stellar rotation.

I produce a plot similar to that of Ruciński (1984) with my own data in Fig. 14, where L_x (Fig. 14a) and L_x/L_{bol} (Fig. 14b) are both plotted against M_V . The lack of detections in the upper right hand corner of Fig. 14a implies that the maximum L_x possible for an M dwarf decreases with spectral type. However, no such drop-off is seen in Fig. 14b. In order to resolve the spread in L_x/L_{bol} , I have plotted Fig. 14 with symbols which are coded by $v \sin i$. One can see that the slow rotators tend to lie at the bottom of the figure, while the rapid rotators are at the top. The relation between L_x and $v \sin i$ was quantified in Chapter 3. By fitting just the M dwarfs, one gets the same exponent with greater error.

Figure 14a. Soft x-ray luminosity vs. absolute visual magnitude for the EMSS M dwarfs. Crossed symbols indicate $v \sin i > 10$ km/s; solid symbols indicate $v \sin i < 10$ km/s; open symbols indicate no rotational measurement. Arrows indicate upper limits on L_x . The two pre-main sequence stars in the sample are denoted by stars. The dashed line represents the upper boundary to x-ray emission found by Ruciński (1984, Fig. 1).

Figure 14b. Ratio of soft x-ray luminosity to bolometric luminosity vs. absolute visual magnitude for the EMSS M dwarfs. Crossed symbols indicate $v \sin i > 10$ km/s; solid symbols indicate $v \sin i < 10$ km/s; open symbols indicate no rotational measurement. Arrows indicate upper limits on L_x . The two pre-main sequence stars in the sample are denoted by stars.

It is most desirable to relate L_x directly to the stellar mass (M). Using the empirical M versus L_{bol} relation of Smith (1983), I derive masses for each star in the sample. A fit to the data (excluding the ambiguous identifications) yields

$$L_x \propto M^{2.5 \pm 0.5}$$

and is shown in Fig. 15.

While for more massive stars, the main sequence relation is $L_{bol} \propto M^{4.0}$, Smith's (1983) results indicate that $L_{bol} \propto M^{2.3}$ for $0.10M_{\odot} < M < 0.43M_{\odot}$. This corresponds to stars later than M2. The similar power law fit above implies that L_x/L_{bol} is roughly constant as a function of mass from M2 through M5, as found by Ruciński (1984). I can say nothing about stars later than M5, since I detect none.

My data supports Ruciński's contention that the energy which powers M dwarf coronae is not drawn solely from rotational energy. If it were, then one would expect $L_x \propto M$ since $E_{rot} = I\omega^2/2$ and the moment of inertia, I , is proportional to M . Instead, L_x depends on mass in a similar manner as L_{bol} , thus suggesting an origin for the energy which drives the corona that is proportional to the thermonuclear energy of the star. Unfortunately, no specific theory yet exists which explains how thermonuclear energy generated in the core could be converted ultimately into coronal x-rays.

Making use of the data in Chapter 4, I note that the fraction of all M dwarfs with $\log L_x > 27.8$ increases as one moves to later spectral type. This is similar to the behavior of the ratio of Me to M dwarfs, first pointed out by Joy and Abt (1974) and later confirmed by Stauffer and Hartmann (1986). This suggests that the local population of coronally active M dwarfs are, in

Figure 15. Soft x-ray luminosity vs. stellar mass for the EMSS M dwarf subsample. The solid line represents a least squares fit (slope = 2.5) to the data, excluding upper limits and the PMS stars.

fact, the Me dwarfs. Since it appears that the overall fraction of M dwarfs which exhibit strong x-ray emission increases with decreasing mass, we must reconcile this result with the fact that L_x appears to decrease with decreasing mass.

This behavior can be explained if the spin-down timescales are longer for lower mass dwarfs, as first suggested by Stauffer *et al.* (1984) after examining the rotational velocity distributions of main-sequence stars in clusters. These authors suggest that loss of angular momentum due to winds after a star reaches the main sequence spins down only its outer convective envelope. The size of the convective envelope with respect to the entire star increases with decreasing total mass. Thus, it should take longer for lower mass stars to spin down. My data represent observational evidence for this scenario among the field stars. Therefore, since one would expect coronal and chromospheric activity to continue in M dwarfs for a longer period of time than in more massive dwarfs, it is quite reasonable to discover that almost half of all early M dwarfs are x-ray bright.

Limits on Late M Dwarfs

As was mentioned earlier, no dwarfs later than M5 were detected in my sample. There can only be two reasons for this. Either the late M dwarfs emit x-rays at greatly reduced levels, or there is a paucity of late M dwarfs. I consider the latter possibility first.

The luminosity function of M dwarfs reaches a fairly well-defined peak at $M_V \sim 13$ in all recent determinations, but is not well known for spectral

types of M5 and later (i.e. $M_V \geq 15$). Recent determinations of the low-mass luminosity function are summarized by Reid (1987), who adopts an “averaged” luminosity function from all sources, including samples of nearby stars, those derived from proper motion catalogues, and those obtained from red color surveys. The space density of late M dwarfs with $15.5 < M_V < 20$ from Reid’s adopted luminosity function is 23.5 M dwarfs per thousand pc^3 .

It is difficult to assign an uncertainty to this space density. The numbers in the individual magnitude bins are quite small, and there are systematic problems with both the local samples and with the color selected samples. There are two qualitative differences in the luminosity functions determined from the two approaches (summarized in the review by Liebert and Probst 1987). First, the nearby star/proper motion samples indicate a significantly shallower decline from the peak near $M_V \sim 13$ than do the color surveys of Reid and Gilmore (1984) and Hawkins (1986). In particular, the sample of known stars within 5.2 pc of the Sun has a substantially higher space density at $M_V > 15$ (Dahn, Liebert, and Harrington 1986) than is indicated in Reid and Gilmore (1984). Secondly, the Hawkins (1986) color survey (see also Reid 1987) indicates that the LF may turn sharply upwards again near the visible limit ($M_V \sim 19$). This is in mild conflict with results from the nearby star/proper motion samples, and is of somewhat questionable statistical significance. However, if the upturn is real, Hawkins (1986) argues that it represents the visible, high luminosity “tail” of a large population of substellar mass brown dwarfs. It is interesting to consider the possibility that the bulk of such a population might be undetectable at the optical wavelengths used for the EMSS identifications, but might include strong x-ray emitters! These

completely convective stars could maintain strong x-ray fluxes for substantially longer times, for the same reasons discussed in the previous section. But if brown dwarfs were proven to be x-ray emitters, then the ultimate energy source for coronal x-rays could not be the thermonuclear reservoir. That there are relatively few such x-ray sources (outside of binary systems) is indicated by the absence of unidentified "blank field" sources in the published MSS. Moreover, the actual failure to find very late (low mass) M dwarf counterparts in this investigation constitutes evidence that significant numbers of brown dwarfs do not exist which are strong x-ray sources.

At this point in the discussion, I must mention the limit imposed on my sampling volume by the optical identification criterion that $m_v < 16$ for stellar x-ray sources which I used in defining the sample (Chapter 2, p. 27). This matter is insignificant for dwarfs earlier than M5 and giants since the volume of space surveyed for these stars at a limiting visual magnitude of 16 is far greater than the volume of space surveyed for these same stars at the limiting x-ray flux of the EMSS. However, these two volumes are of comparable size when one considers the late M dwarfs. I do not believe that dwarfs later than M5 were preferentially excluded from my sample for the following reason. Late M dwarfs are extremely red and, unless they are very nearby, will only appear on the POSS red plate. Throughout the optical identification process for the entire EMSS, extremely red (as well as blue) objects were assigned top priority for spectroscopic observation and were observed. Indeed, three of the M dwarfs in my sample have $m_v > 16$. Therefore, there is really no stringent limit at $m_v = 16$ for the M dwarfs in my sample.

Thus, I utilize the “averaged” space density of late M dwarfs – 23.5 per thousand pc^3 calculated from Reid (1987), recognizing that it could be seriously in error, perhaps by as much as a factor of two. Of course, even if the volume density of these objects were known accurately, the expected x-ray emissivities of these stars are very uncertain. Let us consider the possibility, for which strong arguments were already advanced by Bookbinder (1985), that late M dwarfs emit considerably lower x-ray luminosities than do earlier M types.

Considering all single M dwarfs in his volume limited sample, Bookbinder (1985) found a $\log \langle L_x \rangle$ of 28.73 for young disk and 27.98 for old disk stars. At these luminosities, my EMSS subsample covers 3870 and 265 pc^3 of space, respectively. In 3870 pc^3 , there are 91 late M dwarfs predicted from the averaged luminosity function of Reid (1987). With such a large number, one would expect some young disk stars, yet we detect none. In 265 pc^3 , 6 late M dwarfs are expected, yet we detect none. This argument shows that late M dwarfs, both old and young disk, have values of L_x well below the mean value for higher masses.

This result is not surprising, since the data for the early M dwarfs shows a decrease in L_x with mass. But is the drop in late M dwarf x-ray emission just an extrapolation of the L_x -mass relation derived in the last section? Does L_x continue to decrease with L_{bol} ? Or is there a decidedly greater drop in L_x than that for L_{bol} ? If I extrapolate the L_x -mass relation down to $0.08 M_\odot$, I predict $\log L_x = 27.38$ as an upper limit to late M dwarf coronal emission. A volume of 42.5 pc^3 is sampled by my survey at a luminosity level of $\log L_x = 27.45$ and this is expected to contain only one late M dwarf. Since it

is apparent that the late M dwarfs emit at luminosities below this level, I have sampled a volume of space insufficient to contain even one of these stars. Therefore, I can not answer the questions above since the x-ray fluxes involved are below my sample's sensitivity limits.

Relationship Between Chromospheric and Coronal Activity

The appearance of Ca II H & K and H_α in emission among M dwarfs indicates the presence of a chromosphere. So when considering a sample of M dwarfs selected by virtue of their strong coronal activity, it is not surprising to find that they also have active chromospheres. Some 93% of the M dwarfs in the sample are classified as Me. However, an H_α absorption profile can also be indicative of an active chromosphere, but one of smaller electron density (Cram and Giampapa 1987).

Of the 2 non-Me stars in the sample, one shows no H_α at low resolution and one has no H_α feature at echelle resolution. The latter is Gliese 900, which was recently proposed by Bopp (1987) to be a "marginal" BY Draconis star. BY Dra stars are flare Me dwarfs whose photometric variations are attributed to the passage of dark spots on the rotating stellar surface. Gliese 900 has a chromosphere at an intermediate activity level, sufficient to fill-in the H_α absorption profile, yet not enough to show H_α in emission. Giampapa, Cram, and Wild (1988) confirm this intermediate status for Gliese 900 through analysis of the Ca II H & K lines. The other case (1E0444.9-1000) is too faint to detect the continuum at echelle resolution. Therefore, it is not known whether it shows H_α in absorption or weakly in emission.

In order to investigate the empirical relationship, if any, between chromospheric and coronal activity, I compare L_x with the levels of chromospheric H_α and Ca II K emission. Rather than utilize flux at the surface of the star, thus introducing the uncertainties of the Barnes-Evans relation, we have decided to treat the chromospheric data in the same manner as the x-ray data and calculate the absolute stellar luminosity for both lines, again assuming isotropic emission. This is not a bad assumption for M dwarfs since their filling factors for activity regions are quite high (Giampapa 1985). Schrijver and Rutten (1987) have suggested that flux density at the surface of the star is the appropriate quantity to use when comparing chromospheric and coronal emissions. Their principal objection to using luminosity is that it introduces dependences upon stellar radius. This is not a problem with this study, since I am treating only dwarfs. Furthermore, I did compute surface flux in the manner prescribed by Schrijver (1983) and found no improvement in the scatter of the diagrams presented below. Moreover, in my procedure, any errors in the assigned distances cancel in the comparisons.

Fig. 16 a), b), and c) are log-log scatter diagrams of L_x versus L_{H_α} , L_x versus L_{CaIIK} , and L_{CaIIK} versus L_{H_α} for the Me dwarfs in the sample. Since M flare stars are known to have variable chromospheric and coronal emission, and the various data were taken at different times (especially the photometry which was used to calibrate the line fluxes), it would be inappropriate to plot error bars and try to make a formal fit to the data. However, a definite correlation can be seen in Fig. 16. M dwarfs with higher x-ray luminosities also radiate more at Ca II K and H_α . Skumanich *et al.* (1984) have already shown this for H_α . Their result was $\Delta L_{H_\alpha} = 0.2 L_x$. I have drawn this relation

in Fig. 16a. My data deviates from this relation at the high luminosity end, but this could be a result of catching some stars in flare. $\langle L_{H\alpha}/L_x \rangle$ for the sample is 0.15.

One would like to get some qualitative idea of the slopes of the relations in Fig. 16. However, in the manner which they are plotted, any errors in the distance measurements will tend to bias the slope towards a value of 1. Therefore, I consider the same relations, but with each quantity ratioed to L_v to take out any distance (as well as radius) dependences. This is equivalent to plotting f_x/f_v , etc. Simple linear regressions give slopes of:

- a) 0.70 for H_α versus x-rays
- b) 0.50 for Ca II K versus x-rays
- c) 1.03 for H_α versus Ca II K

Looking at the information above, it seems reasonable that H_α is more sensitive to L_x than is Ca II K. The hypothesis that the chromospheres of M dwarfs are formed by x-ray heating from the corona instead of mechanical deposition of energy from below was put forward by Cram (1982). The H_α line is formed at a higher level in the chromosphere than the Ca II lines (Cram and Mullan 1979; Giampapa, Worden, and Linsky 1982), so one would expect the influence of coronal x-ray emission on its formation to be greater.

Following Giampapa *et al.* (1982), I attempt to test this idea by calculating an energy budget to see if L_x has the appropriate dependence on the chromospheric luminosity (L_c). For each M dwarf with H_α , Ca II K, and unambiguous L_x measurements, I multiply $L_{H\alpha}$ by 1.78 to allow for flux from the entire Balmer series and multiply L_{CaIIK} by 1.83 to include Ca II H. I then ratio the sum to L_x and find a $\langle L_{Balmer+CaII}/L_x \rangle$ of 0.40. From data of

Figure 16a. Soft x-ray luminosity vs. chromospheric H_α luminosity for the EMSS M dwarfs. Crossed symbols indicate $v \sin i > 10$ km/s; solid symbols indicate $v \sin i < 10$ km/s; open symbols indicate no rotational measurement. Arrows indicate upper limits on L_x . The pre-main sequence stars in the sample are denoted by stars. The solid line represents the relation $\Delta L_{H_\alpha} = 0.2 L_x$ which was found by Skumanich *et al.* (1984).

Figure 16b. Soft x-ray luminosity vs. chromospheric Ca II K line luminosity for the EMSS M dwarfs. Crossed symbols indicate $v \sin i > 10$ km/s; solid symbols indicate $v \sin i < 10$ km/s; open symbols indicate no rotational measurement. Arrows indicate upper limits on L_x . The pre-main sequence stars in the sample are denoted by stars.

Linsky *et al.* (1982), I calculate that $L_{\text{Balmer}+\text{CaII}}/L_c \approx 0.77$ for the three Me dwarfs for which they have both optical and IUE data. Therefore, assuming all Me dwarfs radiate from the chromosphere in the same proportions, then $\langle L_c/L_x \rangle \sim 0.52$ for my sample.

The result that $\langle L_c/L_x \rangle < 1$ is consistent with the model of coronal x-rays as the dominant source of chromospheric heating, assuming all the important contributors to chromospheric radiative cooling have been identified. Conversely, this result may be a manifestation of a common mechanism simultaneously forming a chromosphere and corona (Skumanich 1986). Such a mechanism must be more efficient at heating the corona than the chromosphere given that $L_x > L_c$.

The H_α and Ca II K data are plotted in Fig. 17 in the same format as Fig. 14. It shows that H_α luminosity does not drop off as quickly with L_{bol} as do L_x and L_{CaIIK} . But of more interest is the fact that the scatter due to rotation is smaller in Fig. 17 than in Fig. 14. This could be the result of a "saturated" chromosphere as described by Skumanich (1986,1985). Beyond a rotational velocity of about 5 km/sec, the Me dwarf reaches a maximum efficiency in turning turbulent convective energy into magnetic energy, so that Me dwarfs of the same mass will radiate the same chromospheric luminosities, regardless of rotation rate (age). Skumanich and MacGregor (1986) give the saturation value for Ca II H & K as $R'_{HK} = 1.07 \times 10^{-4}$, where $R'_{HK} \equiv \Delta L_{HK}/L_{\text{bol}}$. My data indicates that $\langle L_{\text{CaIIK}}/L_{\text{bol}} \rangle = 6.03 \times 10^{-5}$. After multiplying by 1.83 to allow for the H line, we find a saturation value of 1.10×10^{-4} , in agreement with Skumanich and MacGregor.

Figure 17a. Chromospheric H_{α} luminosity vs. absolute visual magnitude for the EMSS M dwarfs. Crossed symbols indicate $v \sin i > 10$ km/s; solid symbols indicate $v \sin i < 10$ km/s; open symbols indicate no rotational measurement. The two pre-main sequence stars in the sample are denoted by stars. Notice the decreased scatter due to rotation in Fig. 17 compared to Fig 14.

Figure 17b. Chromospheric Ca II K line luminosity vs. absolute visual magnitude for the EMSS M dwarfs. Crossed symbols indicate $v \sin i > 10$ km/s; solid symbols indicate $v \sin i < 10$ km/s; open symbols indicate no rotational measurement. The two pre-main sequence stars in the sample are denoted by stars. Notice the decreased scatter due to rotation in Fig. 17 compared to Fig 14.

If Ca II is indeed saturated, then these data indicate that this effect is stronger in the chromosphere than in the corona.

Summary

I have presented an x-ray selected, flux limited sample of M dwarfs. Analysis of this sample confirms previous results from analyses of optically selected samples, namely: 1) the x-ray luminosity function at the bright end indicates that 42% of all early M dwarfs have $\log L_x > 27.8$ ergs/s; 2) the x-ray “bright” M dwarfs are the Me dwarfs, though, perhaps, mostly the single Me dwarfs; 3) L_x decreases with L_{bol} , while L_x/L_{bol} remains constant through M5.

The limited kinematic information for the sample indicates that the nearby (< 25 pc) members of the sample belong to the young disk, while rotational velocities indicate that $10^8 \leq \tau \leq 1 - 3 \times 10^9$ yrs. In addition, an examination of the local space density of x-ray bright M dwarfs as a function of mass suggests that the rate at which stellar activity (rotation) decreases on the main sequence decreases for lower mass stars. This result for the field stars agrees with studies of rotation in open clusters.

The survey is not sensitive enough to determine if L_x/L_{bol} remains constant after M5, or whether it drops at the mass where M dwarfs become fully convective. I put an upper limit on x-ray luminosity for late M dwarfs of $\log L_x = 27.45$ ergs/s. Furthermore, if the sharp upturn at $M_V = 19.0$ in the luminosity function of Hawkins (1986) is real and is the visible tail of the brown dwarf distribution, then brown dwarfs can not be strong x-ray emitters.

Finally, I find that L_x correlates with H_α and Ca II K emission from the chromosphere. Coronal x-rays play an important role in the formation of the upper chromosphere, but the formation of the entire chromosphere totally by coronal x-rays can not be ruled out since the estimated total chromospheric luminosity for the whole sample is half the value of L_x .

Chapter 6

Two New FK Comae Candidates

As was mentioned earlier, about half of the stellar binary systems detected by the EMSS are “active” binaries (e.g. RS CVn or W UMa type). These active binaries (along with cataclysmic variables) account for the strongest f_x/f_v sources in the EMSS which are associated with stellar objects. This was first realized by Silva *et al.* (1985,1987) in a pilot study of this dissertation project. These authors obtained echelle spectra of about a dozen of the highest f_x/f_v stellar sources from the published MSS and found most of them to be probable RS CVn or W UMa binaries. One of the stars discussed in Silva *et al.* (1985) was 1E1751.0+7046. They classified the star as K5 IV-V. Their high resolution spectra showed enhanced Ca II H & K emission and significantly broadened spectral lines implying a projected rotational velocity, $v \sin i$, on the order of 30–40 km/sec. These authors could not, on the basis of their data, establish if 1E1751.0+7046 was a binary and, therefore, possibly an RS CVn system. They suggested that it could be a rapidly-rotating pre-main sequence star instead of an RS CVn binary.

Although this object lies outside of my defined subsample of the EMSS, I decided to obtain further radial velocity measurements in order to establish this star’s status as a binary and to look for the Li I feature at 6707 Å in order to test the pre-main sequence hypothesis. In this chapter, I report on the results of these and other optical observations, as well as the detection of this star in the radio region. In addition, I consider another star which is in my defined subsample (1E2349.8–0112) and has similar characteristics. Both

stars are uncatalogued. I discuss the possible membership of these stars in the rare, and controversial, FK Comae class of stars.

Radial Velocities

1E1751.0+7046 was observed on eight separate occasions with the MMT echelle spectrograph. Six of these measurements were taken on six consecutive nights during the last week of July, 1986. 1E2349.8–0112 was observed on ten occasions, four of which were during this same week. The echelle setting was identical to that described in Chapter 2 for the stars in my subsample and the radial velocities were calculated in the same manner. The resulting radial velocity measurements, along with the Heliocentric Julian Date (HJD) of each observation, are given in Table 5.

The radial velocities obtained are nearly the same for each star. Attempts to fit short period (less than 20 days) sinusoidal curves have failed. On the other hand, fitting a constant value to the data yields -14.83 ± 0.83 km/sec for 1E1751.0+7046 with a $\chi^2_\nu = 0.61$. This corresponds to a confidence factor of 75%, which is a reasonable fit. The fit for 1E2349–0112 is even better. Its radial velocity is $+14.66 \pm 0.51$ with a $\chi^2_\nu = 0.37$. This corresponds to a 95% confidence level. Also, a precisely one-day period can be ruled out since the measurements were not all taken at the same fraction of a day. Therefore, these stars have constant radial velocities over a weekly timescale and, perhaps, as much as a year.

The v_{rad} of 1E1751.0+7046, however, is some 5σ lower than the original data of Silva *et al.* (1985), which was taken 3 years earlier with the same

Table 5
Radial Velocity Measurements

HJD (244+)	v_{rad} (km/s)	$\pm$ (km/s)
1E1751.0+7046		
6537.95	-13.10	0.64
6569.81	-14.92	0.63
6635.86	-14.24	1.02
6636.82	-14.82	1.03
6637.65	-14.25	0.71
6638.64	-15.59	0.73
6639.64	-17.00	0.92
6640.64	-16.00	0.81
Data of Silva <i>et al.</i> (1985)		
5503.76	-11.50	0.66
5504.96	- 9.90	0.68
1E2349.8-0112		
6329.86	14.48	0.96
6422.69	14.94	0.92
6447.60	13.78	0.72
6637.99	15.53	0.80
6639.00	12.73	0.75
6640.00	16.58	0.76
6641.00	15.43	0.86
6700.83	15.87	1.15
6998.85	14.31	0.92
7000.93	13.02	1.15

instrument. In order to eliminate any systematic shifts in the zero-point, I rereduced the raw data of the previous observations and calculated the radial velocities in an identical manner to my data. These values, which are also given in Table 5, do not vary significantly from those published in Silva *et al.* (1985). It appears that the radial velocity of 1E1751.0+7046 has shifted by about 4 km/sec over a 3 year period.

These echelle observations have also caused me to question the apparent magnitude (m_v) of 1E1751.0+7046. Stocke *et al.* (1983) report $m_v = 13.1$. However, after many echelle observations of this object, I believed this magnitude to be incorrect. The number of counts per second detected on the reticon array were too great for a 13th. magnitude object. My optical photometry shows that, in fact, $V = 9.61$. Measurements of the stellar image on the POSS, the source for m_v estimates in Stocke *et al.* (1983), yield $m_r \approx 9.7$ and $m_b \approx 10.9$. This suggests no 3.4 magnitude increase between the POSS epoch and now. Rather, the m_v published in Stocke *et al.* (1983) is erroneous.

Other MMT Echelle Observations

1E1751.0+7046 was observed with the MMT echelle spectrograph centered at 6705 Å in order to look for the Li I line at 6707 Å. The only lines detected were a weak Ca I at 6717 Å and Fe I at 6678 Å. In addition, two separate observations taken six months apart and centered at 6560 Å failed to detect H_α in emission. H_α was seen in absorption both times with $EW(H_\alpha) = 0.1$ Å.

Echelle observations of 1E2349.8–0112 show that it has a rotationally broadened H_α absorption profile with $EW(H_\alpha) = 0.2 \text{ \AA}$.

Spectral Type

1E1751.0+7046 was also observed with the IRS system on the #2–0.9 m telescope at Kitt Peak National Observatory. The 831 lines/mm grating was centered at 6000 $\text{\AA}$ in first order, yielding 6.9 $\text{\AA}$ resolution. Both the Mg I b lines and Na I D lines are sensitive to surface gravity in K stars. The line indices for these features which were defined by O'Connell (1973) were computed and compared to his standards. Both the Mg I and Na I features are too strong for K5 III, yet they are too weak for K5 V. This indicates that 1E1751.0+7046 is a K5 IV.

Using Steward 2.3 m telescope, 2 $\text{\AA}$ -resolution spectra in the blue, I have given 1E2349.8–0112 a spectral type of K0 III. The giant classification was made by virtue of the Sr II line which was detected at 4077 $\text{\AA}$.

Radio Observations

1E1751.0+7046 was one of 28 late-type stars from the EMSS which were observed at 6 cm with the Very Large Array (VLA). These observations were carried out on July 19, August 23 and 25, 1985. The array was in the C configuration, with an average of 25 antennae operating for the whole duration of the observations. In this configuration, baselines range from 0.2

to 3.5 km. Each star was observed for about 5 minutes at the frequencies of 4835 and 4885 MHz simultaneously, with bandwidths of 50 MHz. To monitor instrumental and atmospheric phase and gain changes, calibration sources were observed for about 3 minutes at approximately 45 minute intervals. The flux densities were bootstrapped from the flux densities of 3C48 and 3C286, assumed to be 5.36 Jy and 7.41 Jy respectively (Baars *et al.* 1977).

Using the standard VLA reduction programs, the visibility data were carefully checked for deviating amplitudes and phases, which were flagged out. After calibration, the visibility data were gridded onto the u - v plane and Fourier transformed to produce total intensity maps $4' \times 4'$ large and with a pixel size of $1''$. The “dirty” maps were cleaned with the standard Astronomical Image Processing System (AIPS) (Clark 1980) available at the VLA site and at the CfA Computation Facility. The rms noise level achieved in each field was typically ~ 0.2 mJy.

Of the 28 stars observed (which did not include 1E2349–0112), 1E1751.0+7046 was the only one detected. Its flux density at 6 cm is 3.8 mJy. Assuming $M_v \sim 3.5$ for a K5 IV, I estimate a distance somewhere between 150 and 200 pc. If the radio emission is isotropic, then $L_{5GHz} \sim 10^{17}$ ergs/sec Hz.

Discussion

The major difficulty in the analysis of 1E1751.0+7046 and 1E2349.8–0112 is reconciling the rapid rotation rate with the lack of a significant change in radial velocity. For a K5 IV, P_{rot} would be ≤ 7.5 days. This rules out the possibility of 1E1751.0+7046 being a synchronously rotating binary, unless one would want to invoke a mass ratio small enough to make Δv_{rad} less than my measurement error, which is improbable. The slight shift in radial velocity between the 1983 and 1986 observations would seem to suggest a very long-period binary system. The time coverage of the total data set is insufficient to fit a sinusoidal curve with accuracy, but period finding routines can be used to find a set of probable periods. The shortest probable period greater than 100 days for this data set is 401 days, with a peak to peak velocity amplitude of 10 km/sec. From this, I can determine the separation given the mass ratio. Assuming the companion is less massive than 1E1751.0+7046, then a > 0.7 A.U. This is too far away for the unseen companion to have any effect on the evolution of 1E1751.0+7046.

A rather good (88% confidence) sinusoidal fit was made to the 1E2349.8–0112 data with a 61.3 day period and 1.78 km/s amplitude. I do not consider this result to be real since the typical error in measuring v_{rad} is half of the amplitude of variation. In order to cause such a variation, the secondary would have to be a $0.1 M_{\odot}$ star (M6 dwarf) at a distance of 0.1 AU, which is insignificant as an x-ray source since M6 dwarfs are below the EMSS sensitivity limit (see Chapter 5). Furthermore, if such a companion did exist, it could not be in synchronous orbit since the primary, a K0 giant (R

$\sim 16 R_{\odot}$) having $v \sin i = 50$ km/s, has a rotation period on the order of 16 days. Therefore, I feel justified in treating 1E1751.0+7046 and 1E2349.8-0112 as single stars.

I further argue that 1E1751.0+7046 is not a pre-main sequence star because of the lack of Li I in its photosphere, as well as its location ($\ell^{II} = 101^{\circ}.5, b^{II} = 30^{\circ}.8$) away from any known star-forming regions. Thus, I suggest that these stars could be FK Comae stars.

The FK Comae stars (Bopp and Stencel 1981; Collier 1982) appear quite like RS CVn binaries except that they show no evidence of radial velocity variations. It has been suggested that they are the evolutionary successors to the W UMa stars at a point after the two stellar cores have coalesced. The orbital angular momentum is transferred to the stellar envelope. Thus, the star rotates rapidly.

The four known FK Comae stars (excluding UZ Librae, which is a binary; Bopp *et al.* 1984) have $v \sin i$ values between 50 and 100 km/sec. 1E1751.0+7046 and 1E2349.8-0112 have $v \sin i$ values less than this, but greater than the 24 km/sec value measured for the FK Comae-like star in NGC 188 which was recently discovered by Harris and McClure (1985). As these stars age, they lose angular momentum (Webbink 1976). Therefore, one would expect to find a continuum of $v \sin i$ values for the FK Comae stars because of this and because of the distribution in inclination to the line of sight. It is also interesting to note that among the known FK Comae stars (cf. Table 3, Collier 1982), those with the largest $v \sin i$ values are also the earliest in spectral type. HD 32918, a K2 III, has the same $v \sin i$ as 1E2349.8-0112. 1E1751.0+7046 has a spectral type of K5, later than any of the currently

known FK Comae stars. This further indicates that 1E1751.0+7046 would be a more evolved, spun-down FK Comae star.

However, another interpretation is offered by Walter and Basri (1982). They suggest that FK Comae itself is a low mass ratio binary and a unique object. The other members of the class can be explained as single stars that were once rapidly-rotating F dwarfs and have now evolved across the Hertzsprung Gap. We are observing them just after crossing the Gap and before ascending the giant branch. Since these stars would have shallower convection zones than solar-type stars, the magnetic braking mechanism would not be as strong. Therefore, these stars would still retain substantial angular momentum. 1E1751.0+7046 and 1E2349.8-0112 could also fit into this scenario since one would expect rotation rate to decrease with later spectral type.

The one piece of datum which does not fit into the FK Comae picture is the apparent lack of H_α emission. Even I-1 in NGC 188 shows a weak H_α emission core. It has been suggested that FK Comae H_α emission comes from an "excretion" disk of material which is given off by the star as it loses angular momentum (Ramsay, Nations, and Barden 1981). Perhaps 1E1751.0+7046 and 1E2349.8-0112 have already lost their disks or I have just caught them in a low emission state. HD199178, one of the FK Comae stars, at times shows no H_α emission (Bopp 1982). Comparing the H_α profile of 1E1751.0+7046 to those profiles of "normal" K5 stars published by Zarro and Rodgers (1983), I find that its H_α equivalent width is smaller than normal. Both K5 dwarfs and giants typically have $EW(H_\alpha) \sim 0.8 \text{ \AA}$. This would indicate some H_α emission is filling in the photospheric absorption. In any case, 1E1751.0+7046

and 1E2349.8-0112 do have very active coronae as evidenced by their x-ray and, for 1E1751.0+7046, radio flux.

Radio observations of FK Comae itself have recently been published (Hughes and McLean 1987; Florkowski *et al.* 1985; Turner 1985). The $L_{5GHz} \sim 10^{17}$ ergs/sec Hz which I estimate for 1E1751.0+7046 is of the same order of magnitude as the L_{5GHz} quoted by Hughes and McLean (1987) for FK Comae and those maximum luminosities listed for RS CVns by Gibson (1985). Of course, the radio luminosities of these stars vary with flaring activity. The flux density of FK Comae at 6 cm measured by Florkowski *et al.* (1985) is less than the measurement of Hughes and McLean (1987) by a factor of 3. 1E1751.0+7046 was probably observed in the radio while it was flaring.

Although I have not measured other parameters such as spectral index or degree of polarization for this star, RS CVns which exhibit the same 6 cm luminosities are believed to be incoherent gyrosynchotron emitters (Owen *et al.* 1976; Mullan 1985). Indeed, from spectral information, Hughes and McLean (1987) come to the same conclusion for FK Comae. The emission is thought to come from relativistic electrons in coronal streamers which are confined by magnetic fields from photospheric starspots. All I can say about 1E1751.0+7046 is that the one radio datum point which I have is consistent with FK Comae and the RS CVn binaries.

Summary

I have presented optical and radio observations of the serendipitously detected x-ray sources 1E1751.0+7046 and 1E2349.8-0112. I have noted their similarities to the FK Comae class of stars and suggest them as candidates for this class (although as regards 1E1751.0+7046, a somewhat senior member.) However, in order to establish them as members of the class, it will be necessary to obtain photometry to determine their light curves and periods of rotation.

Furthermore, determination of the space density and distribution of these FK Comae type stars would be an important piece of information in trying to understand the evolutionary status of these objects. Should these candidates from the EMSS turn out to be *bona fide* members of the class, then the total number of known FK Comae stars will have increased by 50%. In light of this statement, I suggest that an efficient way to search for new FK Comae type stars is through x-ray sky surveys.

Appendix A

My EMSS Stellar Subsample: Classifications, Cross-references, and Comments

EMSS	MK Class	HD	SAO	Other	Comments
0002.9+1602	F5 V	42	91699		
0007.5+1051	B8n V	560	91750	34 Psc	EXO
0009.9+1417	G5 V		91772		RS
0011.6+0840	K0 V				
0031.9-0646	F4 V	3126	128830		
0036.1+3309	G2 V				
0039.2-0206	K4 VI				
0103.6+3206	F6 V				
0105.3+3144	F5 IV	6680	54445	78 Psc	RS
0132.5+2101	F9 V				
0134.4+2027	F9 V	9902	74827		EXO
0205.5+1454a	M4e V				EXO; pair
0205.5+1454b	M5e V				sep. = 2"
0215.0+1813	F0 V	14147	92873		
0232.5+2321	M3e V				
0233.8+0649	K7e V				
0234.4+0641	M5e V				
0234.8-0210	G9 V				
0234.2-0321	K2 V	16287	130011		
0235.6+1631	G1 V				
0241.7+1045a	M0e V				unrelated
0241.7+1045b	M5e V				sep ~ 20"
0244.9-0024	G9 V		130113		EXO; RS
0255.3+2018	K3 PMS				also Syf 1
0257.4+0733	G6 III	18632	110894		
0300.2-1528	G8 V	18955	148731		ClG NW of EC
0307.5+1424	G6 V				
0308.4+1413	F8 V				
0315.8-1955	K5 V				RS
0318.6-1926	K7 V				
0333.1+0607	F6 V				
0337.6-0202	G9 V	22853	130647		
0348.2-1404	K0 IV				radio 3" out of EC
0356.9+1011	F5 V	25102	93710		
0401.7+2150a	M3e PMS				Taurus; pair
0401.7+2150b	M3e PMS				sep ~ 5"
0402.4+2152	G5 V	25680	76438	GL 160	
0411.5+2327	G5 V	26736	76516		

EMSS	MK Class	HD	SAO	Other	Comments
0429.4+1755	K8e PMS				Taurus
0430.7+1754	B9n IV	28867	94002		
0438.6+0213	F9 V				RS or W
0443.8-1006	K7 V				
0443.9-0952	M5e V				
0444.9-1000	M0 V				
0448.4+1058	F8 V	30810	94163		
0451.7-0305	F8 V				RS or W; also 18 mag gal in EC
0502.9-1204	M4e V			LP 716-35	
0505.0-0527	G9 IV				RS
0509.5-1607	K7 V				
0538.6-0949	F8 V	37827	132453		
0657.5+7518	K1 IV		6052		
0657.6+7529	K1 V	51066	6053		
0730.3+6546	F6 V-IV	59581	14241		HRI
0758.8+1411	F6 IV	65916	97486		
0801.7+2425	K1 V-IV				unresolved pair
0810.2+6305	G7 V-IV		14468		
0815.3+7433	M3e V				
0816.2+7449	M2e V				
0820.2+0201	G6 V	70573	116694		
0824.0+2944	F8 V	71208	80190		
0830.3+1126	G0 III	72429	97905		
0830.7+2828	G4 V				also F6 V in EC
0842.7+1900	F2 V	74607	98098		
0851.2+2025	F7 V		80493		EXO
0907.0+0654	M4e V				
0920.6+7838	G6 V				assoc with SAO 6845 (G3 V)
0923.0-0610	A3 V	81421	136833		
0924.3+3942	K8 V			GL 343.1	
1019.8-1016	K5 V				
1022.3+1259	A2 V	90208	99104		
1022.6+1121	G6 V				RS
1049.5-0849	G7 V				RS
1050.2-0925	M0e V				
1058.2+1220	M5e V				
1112.6+1311	M3e V				
1127.9-1502	G0 V	100022	156720		RS; SB2
1153.0+2344	G2 V				peripheral ClG
1208.6+3924	F5 V	105881	62883		RS or W
1211.8+1206	G8 V	106400	100003	AH Vir	W UMa
1213.9+3809	G2 IV				RS; F8 V at EC edge

EMSS	MK Class	HD	SAO	Other	Comments
1215.1+6932	K7 V			VV Dra	
1216.1+2818	M2e V				
1222.5+2549	F7 V	108102	82295	Hall #64	RS CVn
1224.7+7531	M0e V				CIG SE of EC
1254.9+0142	F4 V	112542	119684		
1255.3+3529a	M0e V			GL 490A	
1255.3+3529b	M4e V			GL 490B	
1330.6-0811	G0 V	117860	139405		EXO
1350.8+1810	G8 III	121107	100751	7 Boo	
1404.5+5502	M0e V				5" from K5 V
1440.4+5213	F3 V	129674	29248		RS
1441.4+5222	M1.5e V				galaxy in EC
1441.7+5208	G2 V	129920	29254		also G8 V in EC
1457.0+2108	F8 V				galaxy in EC
1457.0+2226	M2e V				
1520.8-0625	K0 III	136905	140499	Hall #78	RS CVn
1521.2+3027	F8 V	137107	64673	GL 584	
1530.6+1342	K8e V				
1533.0+0919	K4e V				
1534.7+5448	A0 V	139493	29588		
1548.8+1125	K5 V-IV				
1559.8+1753	K3 V				
1559.9+4202	G9 III				
1601.1+4119	K3 V				RG at EC edge
1615.0+3114	G0 V				W
1621.5+2640	G0 V				ambig, 4 stars & radio in EC
1634.8+2638	F5 V	149931	84485		
1635.0+2651	F6 V	149973	84487		
1640.1+5349	M0e V				
1640.6+6224	B8e V	151067	17187		
1654.0+3515	G2 V				W
1654.4-0415	M4e V			LHS 3255	
1704.3+5432	F6 V	154905	30239	μ Dra	
1709.2+5432	K6 V		30275	GL 659	SAO 30274 (K6 V) at EC edge
1737.3+6847	F5 V	160922	17576	ω Dra	
1806.1+6944	F9 V				W
1810.4+6940	K2 V	167605	17800		EXO
1839.6+8002	M4e V			LP 25-2	
1849.2+7953	A9 V	175938	9256		
2034.9+7532	F8 V				F8 V in EC
2038.3-0046	F8 V	197010	144692		W
2045.4+7523	F8 V	198547	9870		

EMSS	MK Class	HD	SAO	Other	Comments
2113.4+0517	K4 V-IV				
2116.7-1042	G2 V				RS
2119.7+1655	F6 V				W
2136.1-1509	G1 V				
2148.3+1420	K3 V-IV				RG in EC
2253.8+2036	K7 V				
2255.7+2039	M3e V				ClG in EC
2332.5+0119	M1 V			GL 900	
2335.3+0305	F5 V	222111	128293		
2346.9+1842a	M0e V				unrelated
2346.9+1842b	M3e V				sep ~ 20"
2349.8-0112	K0 III				FK
0326.7-2008	F4 V				
0327.2-2416	K7 V-IV	21703	168581		
0535.7-2839	F4 V	37484	170610		
0535.8-2843	F7 V	37495	170613	ν Col	
0956.8-2225	K2 V		178272		
1110.8-2611	A2 V	97528	179648		
1436.9-2628	F6 V		182743		
1552.0-2338	G3 PMS	142361	183920		
1559.2-2232	B9 V	143600	184045		
1751.0+7046	K5 IV				FK

Abbreviations used in Appendix A

ClG – cluster of galaxies

EC – x-ray positional error circle

EXO – x-ray position confirmed by EXOSAT

FK – FK Comae candidate

HRI – x-ray position confirmed by *Einstein* High Resolution Imager

RG – radio galaxy

RS – RS CVn binary candidate

SB2 – double line spectroscopic binary

W – W UMa binary candidate

Appendix B

X-ray Data from the *Einstein* Imaging Proportional Counter

EMSS	f_x (10^{-13} ergs cm $^{-2}$ s $^{-1}$)	$\log \left(\frac{f_x}{f_*} \right)$	HR
0002.9+1602	3.29 ± 0.51	-3.68	0.32
0007.5+1051	8.86 ± 0.85	-4.48	-0.17
0009.9+1417	27.60 ± 3.81	-2.79	0.27
0011.6+0840	5.09 ± 0.96	-2.31	-0.41
0031.9-0646	11.00 ± 1.18	-3.86	-0.21
0036.1+3309	6.20 ± 1.50	-2.71	-0.08
0039.2-0206	1.15 ± 0.27	-2.47	0.49
0103.6+3206	1.84 ± 0.40	-3.31	0.28
0105.3+3144	3.19 ± 0.56	-4.63	-0.11
0132.5+2101	1.36 ± 0.27	-3.19	-0.52
0134.4+2027	9.85 ± 0.55	-3.17	0.16
0205.5+1454a	7.36 ± 1.29	-1.04	-0.27
0205.5+1454b	1.80 ± 0.32	-0.64	-0.27
0215.0+1813	1.99 ± 0.37	-4.42	-0.24
0232.5+2321	7.19 ± 1.37	-1.29	-0.71
0233.8+0649	1.81 ± 0.33	-2.12	0.31
0234.4+0641	1.79 ± 0.35	-0.98	-0.14
0234.8-0210	4.41 ± 0.53	-2.83	0.26
0234.2-0321	3.81 ± 0.84	-3.81	0.08
0235.6+1631	1.16 ± 0.21	-1.97	0.61
0241.7+1045a	17.76 ± 2.18	-1.96	0.06
0241.7+1045b	17.76 ± 2.18	-0.22	0.06
0244.9-0024	11.60 ± 1.69	-2.72	0.10
0255.3+2018	2.83 ± 0.48	-2.24	0.32
0257.4+0733	3.01 ± 0.49	-3.97	-0.46
0300.2-1528	2.22 ± 0.55	-3.91	-0.68
0307.5+1424	1.11 ± 0.24	-3.41	0.24
0308.4+1413	4.21 ± 0.43	-2.45	0.44
0315.8-1955	7.57 ± 0.93	-2.44	0.37
0318.6-1926	9.20 ± 0.75	-2.56	-0.05
0333.1+0607	1.48 ± 0.28	-3.34	0.66
0337.6-0202	3.21 ± 0.74	-3.92	-0.15
0348.2-1404	5.92 ± 1.26	-2.60	0.05
0356.9+1011	6.25 ± 0.59	-4.29	-0.16
0401.7+2150a	4.99 ± 0.46	-0.95	0.16
0401.7+2150b	4.99 ± 0.46	-0.90	0.16
0402.4+2152	14.59 ± 1.14	-4.11	-0.34
0411.5+2327	4.13 ± 1.03	-3.79	-0.13

EMSS	f_x (10^{-13} ergs cm $^{-2}$ s $^{-1}$)	$\log \left(\frac{f_x}{f_*} \right)$	HR
0429.4+1755	7.65 ± 1.22	-1.90	0.20
0430.7+1754	27.50 ± 2.86	-3.69	0.14
0438.6+0213	6.95 ± 1.13	-2.54	0.38
0443.8-1006	1.58 ± 0.27	-2.70	-0.28
0443.9-0952	1.30 ± 0.29	-0.96	0.06
0444.9-1000	1.61 ± 0.00	-1.10	0.70
0448.4+1058	8.86 ± 1.46	-3.98	-0.04
0451.7-0305	7.05 ± 1.26	-0.71	0.30
0502.9-1204	2.53 ± 0.26	-2.04	-0.12
0505.0-0527	67.21 ± 2.62	-1.73	0.31
0509.5-1607	2.74 ± 0.61	-1.72	-0.15
0538.6-0949	2.83 ± 0.74	-3.73	1.00
0657.5+7518	3.69 ± 0.70	-3.75	0.02
0657.6+7529	14.32 ± 1.26	-3.57	0.23
0730.3+6546	5.05 ± 0.54	-3.58	0.14
0758.8+1411	1.98 ± 0.38	-3.25	0.97
0801.7+2425	2.31 ± 0.41	-2.30	-0.15
0810.2+6305	1.49 ± 0.34	-3.71	-0.57
0815.3+7433	1.11 ± 0.27	-0.82	0.93
0816.2+7449	2.93 ± 0.45	-1.85	-0.35
0820.2+0201	2.84 ± 0.47	-3.66	-0.09
0824.0+2944	2.65 ± 0.42	-3.76	-0.07
0830.3+1126	6.02 ± 0.87	-3.68	-0.01
0830.7+2828	1.40 ± 0.33	-2.34	-0.57
0842.7+1900	2.13 ± 0.41	-4.57	-0.01
0851.2+2025	2.46 ± 0.24	-3.81	0.01
0907.0+0654	5.53 ± 0.67	-1.55	-0.08
0920.6+7838	3.77 ± 0.64	-3.56	-0.21
0923.0-0610	9.00 ± 0.00	-3.52	0.06
0924.3+3942	4.57 ± 0.55	-3.05	-1.00
1019.8-1016	3.01 ± 0.66	-2.83	-0.25
1022.3+1259	2.31 ± 0.00	-3.97	0.02
1022.6+1121	6.89 ± 1.34	-2.58	0.10
1049.5-0849	4.36 ± 0.99	-2.52	0.23
1050.2-0925	6.61 ± 1.51	-1.82	-0.14
1058.2+1220	2.64 ± 0.59	-0.82	-0.1
1112.6+1311	1.91 ± 0.42	-1.29	0.04
1127.9-1502	8.81 ± 1.81	-2.93	-0.12
1153.0+2344	6.34 ± 1.10	-1.81	-0.20
1208.6+3924	1.35 ± 0.20	-4.29	-0.05
1211.8+1206	8.28 ± 0.99	-3.06	0.09
1213.9+3809	0.91 ± 0.21	-1.56	1.00
1215.1+6932	2.52 ± 0.30	-3.31	-0.36
1216.1+2818	1.11 ± 0.24	-1.40	0.09

EMSS	f_x (10^{-13} ergs cm $^{-2}$ s $^{-1}$)	$\log \left(\frac{f_x}{f_v} \right)$	HR
1222.5+2549	13.63 ± 1.95	-3.26	-0.04
1224.7+7531	1.45 ± 0.27	-2.54	0.30
1254.9+0142	2.77 ± 0.51	-4.40	-0.19
1255.3+3529a	21.34 ± 2.09	-2.10	-0.12
1255.3+3529b	21.34 ± 2.09	-1.04	-0.12
1330.6-0811	8.64 ± 0.82	-3.81	-0.15
1350.8+1810	5.57 ± 1.03	-4.60	0.53
1404.5+5502	3.94 ± 0.70	-1.44	-0.17
1440.4+5213	1.98 ± 0.37	-4.35	0.02
1441.4+5222	1.41 ± 0.33	-1.87	0.26
1441.7+5208	4.15 ± 0.47	-3.73	-0.28
1457.0+2108	2.01 ± 0.49	-2.86	0.38
1457.0+2226	4.73 ± 0.51	-1.12	0.05
1520.8-0625	6.81 ± 1.27	-3.87	0.10
1521.2+3027	2.62 ± 0.58	-4.97	-0.65
1530.6+1342	13.69 ± 2.08	-1.53	0.10
1533.0+0919	5.52 ± 1.12	-2.22	0.34
1534.7+5448	3.90 ± 0.94	-4.74	-0.10
1548.8+1125	5.77 ± 0.80	-1.76	0.38
1559.8+1753	1.66 ± 0.31	-2.97	0.08
1559.9+4202	1.50 ± 0.35	-3.34	-0.16
1601.1+4119	1.14 ± 0.25	-2.02	0.17
1615.0+3114	1.23 ± 0.21	-2.52	0.82
1621.5+2640	2.67 ± 0.50	-1.42	0.12
1634.8+2638	11.58 ± 0.46	-3.37	0.09
1635.0+2651	4.87 ± 0.30	-3.74	-0.13
1640.1+5349	3.02 ± 0.40	-2.22	-0.18
1640.6+6224	5.46 ± 0.98	-4.00	0.41
1654.0+3515	1.77 ± 0.34	-3.34	0.14
1654.4-0415	27.39 ± 2.44	-1.28	-0.02
1704.3+5432	23.23 ± 2.16	-3.93	-0.29
1709.2+5432	5.86 ± 1.13	-3.33	-0.31
1737.3+6847	18.64 ± 1.60	-4.44	-0.34
1806.1+6944	1.38 ± 0.19	-3.30	0.47
1810.4+6940	7.81 ± 0.41	-3.31	-0.29
1839.6+8002	7.80 ± 0.48	-1.45	-0.30
1849.2+7953	2.70 ± 0.25	-4.67	0.09
2034.9+7532	2.74 ± 0.41	-2.56	0.22
2038.3-0046	9.35 ± 0.52	-2.92	0.16
2045.4+7523	3.00 ± 0.33	-3.58	-0.1
2113.4+0517	2.39 ± 0.45	-2.15	0.43
2116.7-1042	1.13 ± 0.27	-2.73	-0.29
2119.7+1655	1.72 ± 0.40	-2.70	0.59
2136.1-1509	2.43 ± 0.46	-1.80	0.36

EMSS	f_x (10^{-13} ergs cm $^{-2}$ s $^{-1}$)	$\log \left(\frac{f_x}{f_\odot} \right)$	HR
2148.3+1420	3.29 ± 0.55	-1.35	-0.12
2253.8+2036	4.43 ± 0.53	-1.47	-0.31
2255.7+2039	2.12 ± 0.38	-0.98	0.46
2332.5+0119	11.05 ± 2.12	-2.77	-0.32
2335.3+0305	4.18 ± 0.49	-3.81	-0.08
2346.9+1842a	8.04 ± 1.29	-1.90	-0.33
2346.9+1842b	8.04 ± 1.29	-1.09	-0.33
2349.8-0112	5.12 ± 1.08	-2.63	0.04
0326.7-2008	3.81 ± 0.69	-3.49	-0.25
0327.2-2416	34.29 ± 2.26	-2.50	-0.09
0535.7-2839	2.75 ± 0.24	-4.32	-0.19
0535.8-2843	7.54 ± 0.36	-4.63	-0.01
0956.8-2225	26.07 ± 2.24	-2.53	-0.09
1110.8-2611	1.85 ± 0.30	-4.48	0.01
1436.9-2628	6.65 ± 1.34	-3.13	-0.17
1552.0-2338	51.10 ± 1.23	-2.41	0.07
1559.2-2232	8.03 ± 1.28	-3.53	0.37
1751.0+7046	25.40 ± 2.29	-2.37	0.41

Appendix C

Kinematic Data Derived from the Echelle Spectroscopy

EMSS	$v \sin i$ (km/s)	HJD (244+)	v_{rad} (km/s)	Comments
0002.9+1602	12 ± 2.0	6636.98 6688.76 6689.76	-11.87 ± 0.97 8.56 ± 1.04 9.00 ± 0.85	binary
0007.5+1051	275	...	...	v_{rot} from BSC
0009.9+1417	22 ± 3.0	6636.99 6688.78 6689.76	35.19 ± 0.87 46.36 ± 0.63 -80.18 ± 0.59	binary RS
0011.6+0840	22 ± 4.4	6689.79 6997.99 6999.00	-9.19 ± 1.67 43.77 ± 1.81 24.21 ± 0.81	binary Ke
0031.9-0646	26 ± 2.0	6688.81 6689.81	11.77 ± 0.71 12.24 ± 0.63	
0036.1+3309	26 ± 1.5	6447.59 6700.84	4.46 ± 0.55 2.13 ± 0.88	
0039.2-0206	< 10	6329.92 6447.67 6636.97	-8.96 ± 1.40 -7.12 ± 1.89 -13.07 ± 2.73	
0103.6+3206	39 ± 4.7	6700.86 6997.99	13.40 ± 1.21 14.20 ± 0.78	
0105.3+3144	68 ± 20.5	6688.82 6689.81	19.40 ± 1.64 1.94 ± 2.45	binary RS
0132.5+2101	28 ± 1.4	6689.85 6700.85	5.99 ± 0.45 5.16 ± 0.80	
0134.4+2027	11 ± 0.4	6636.00 6688.84 6689.82	54.28 ± 0.87 40.75 ± 1.27 40.80 ± 0.89	binary
0205.5+1454a	< 10	6700.89 6998.93	10.86 ± 1.70 13.44 ± 1.60	unresolved resolved
0205.5+1454b	< 10	6700.89 6998.95	10.86 ± 1.70 12.69 ± 1.69	unresolved resolved
0215.0+1813	24 ± 5.9	6998.00	22.93 ± 2.12	
0232.5+2321	14 ± 4.4	6998.90 7138.82	-13.64 ± 2.62 -11.08 ± 1.53	
0233.8+0649	12 ± 1.5	6700.92 6998.96	11.33 ± 1.34 12.87 ± 1.04	
0234.4+0641	...	...	...	too faint

EMSS	$v \sin i$ (km/s)	HJD (244+)	v_{rad} (km/s)	Comments
0234.8–0210	< 10	6422.71 6447.71 6700.93	3.85 ± 0.69 4.89 ± 0.46 3.57 ± 0.72	binary
0234.2–0321	< 10	6635.99 6688.88 6689.84	13.73 ± 0.96 30.89 ± 0.58 25.68 ± 0.51	
0235.6+1631	< 10	6329.95 6447.70	-53.65 ± 0.92 -53.01 ± 0.74	
0241.7+1045a	28 ± 2.6	6426.82 6447.72 7000.98 7138.84	2.89 ± 0.97 6.17 ± 0.83 3.65 ± 1.00 3.98 ± 1.23	binary
0241.7+1045b	17 ± 4.1	6997.98 7138.84	12.18 ± 2.07 11.50 ± 2.84	
0244.9–0024	17 ± 1.0	6635.98 6688.89 6689.88	27.69 ± 0.93 -7.27 ± 0.59 -54.83 ± 0.46	
0255.3+2018	30 ± 3.5	6700.94 6998.97	-6.26 ± 1.18 -5.03 ± 1.35	binary RS
0257.4+0733	< 10	6635.98 6688.91 6689.89	28.66 ± 0.98 28.46 ± 0.59 28.39 ± 0.52	
0300.2–1528	13 ± 0.5	6688.92 6689.89	33.82 ± 0.56 33.69 ± 0.50	
0307.5+1424	< 10	6447.74 6700.96	19.08 ± 0.62 18.15 ± 0.74	binary RS
0308.4+1413	< 10	6447.73 6700.97	34.86 ± 0.56 35.87 ± 0.92	
0315.8–1955	23 ± 1.5	6447.75 6700.95	17.88 ± 0.62 29.03 ± 0.87	
0318.6–1926	11 ± 1.0	6447.75 6700.95	21.30 ± 0.79 20.34 ± 1.04	binary
0333.1+0607	24 ± 1.5	6447.76 6700.97	10.24 ± 0.63 11.34 ± 0.86	
0337.6–0202	< 10	6688.92 6689.90	14.72 ± 0.42 15.00 ± 0.35	
0348.2–1404	< 10	6689.94 6700.98	19.04 ± 0.94 -71.02 ± 1.16	binary
0356.9+1011	49 ± 3.8	6688.93 6689.90	38.95 ± 1.04 37.56 ± 0.84	
0401.7+2150a	12 ± 2.0	7138.87	14.87 ± 1.43	
0401.7+2150b	...	...	...	v_{rot} from BSC
0402.4+2152	3	...	...	

EMSS	$v \sin i$ (km/s)	HJD (244+)	v_{rad} (km/s)	Comments
0411.5+2327	< 10	6688.94	37.23 ± 0.41	
		6689.91	37.14 ± 0.30	
0429.4+1755	< 10	6689.97	2.64 ± 1.16	binary
		6998.99	24.28 ± 1.00	
0430.7+1754	...	...	...	binary, BSC
0438.6+0213	...	6329.98	11.53 ± 0.96	binary
		6422.75	16.99 ± 2.26	RS or W
		6426.79	47.28 ± 2.03	var line
		6859.61	2.13 ± 2.24	width
		6865.63	13.15 ± 1.51	
		6866.59	10.60 ± 2.44	
		6869.60	7.71 ± 1.46	
		6870.60	9.13 ± 2.37	
		6873.59	5.04 ± 2.52	
0443.8-1006	< 10	6701.01	23.20 ± 1.04	
		7000.99	22.05 ± 0.95	
0443.9-0952	...	...	...	too faint
0444.9-1000	...	...	...	too faint
0448.4+1058	< 10	6688.95	41.04 ± 0.46	
		6689.91	41.29 ± 0.31	
0451.7-0305	...	6330.01	19.68 ± 1.65	binary
		6422.82	4.75 ± 1.62	RS or W
		6447.82	21.55 ± 1.35	var width
0502.9-1204	< 10	6422.86	1.77 ± 0.93	
		6701.02	2.43 ± 1.05	
0505.0-0527	14 ± 0.7	6330.02	0.28 ± 0.85	binary
		6422.83	57.87 ± 0.74	RS
		6426.83	2.04 ± 0.74	P = 8.82 d
		6865.65	46.00 ± 0.60	k = 31.2 km/s
		6866.60	26.60 ± 0.59	$\gamma = 29.5$ km/s
		6869.61	4.51 ± 0.75	
		6870.61	25.93 ± 0.77	
		6870.67	25.99 ± 0.68	
		6873.60	59.18 ± 0.68	
0509.5-1607	11 ± 1.0	7138.89	48.64 ± 0.81	
0538.6-0949	65 ± 5.6	6540.64	19.24 ± 0.82	
		6689.01	16.92 ± 0.95	
		6689.99	20.46 ± 1.15	
0657.5+7518	< 10	6540.65	21.46 ± 1.00	binary
		6573.65	7.65 ± 0.29	
0657.6+7529	43 ± 1.4	6540.66	-19.21 ± 1.00	
		6573.63	-18.22 ± 0.53	
		6689.02	-16.35 ± 0.70	
		6690.00	-18.49 ± 0.57	

EMSS	$v \sin i$ (km/s)	HJD (244+)	v_{rad} (km/s)	Comments
0730.3+6546	17 ± 1.1	6540.66 6573.66	67.04 ± 1.00 73.31 ± 0.61	binary
0758.8+1411	13 ± 1.6	6540.67 6574.63	39.94 ± 1.00 39.26 ± 0.46	
0801.7+2425	< 10	6422.90 6537.64	52.99 ± 1.57 32.93 ± 1.73	unresolved vis. binary
0810.2+6305	< 10	6447.92 6540.68 6573.67	11.34 ± 0.47 10.68 ± 1.00 10.31 ± 0.27	
0815.3+7433	...	...	...	too faint
0816.2+7449	< 10	6422.94 6447.89	8.78 ± 0.84 9.16 ± 0.85	
0820.2+0201	14 ± 1.4	6574.62 7139.06	19.00 ± 0.82 20.01 ± 0.47	
0824.0+2944	< 10	6574.64 7139.07	36.28 ± 0.33 41.78 ± 0.55	binary
0830.3+1126	14 ± 0.7	6540.63 6574.65	79.34 ± 1.00 79.82 ± 0.44	
0830.7+2828	< 10	6426.90 6540.72	-36.56 ± 0.75 -35.08 ± 1.00	
0842.7+1900	< 10	6574.65 6530.67	52.06 ± 0.47 103.23 ± 1.00	binary
0851.2+2025	26 ± 1.7	6540.62 6574.66	30.13 ± 1.00 30.78 ± 0.64	
0907.0+0654	< 10	7138.95	2.89 ± 0.97	
0920.6+7838	< 10	6573.69	-10.75 ± 0.33	
0923.0-0610	19 ± 3.0	6574.68	18.57 ± 1.33	
0924.3+3942	< 10	6422.96 6537.68 6569.65	-82.06 ± 1.32 28.85 ± 1.31 -38.03 ± 1.39	binary
1019.8-1016	< 10	6422.98 6537.69 6540.75 6569.71	15.07 ± 0.95 14.18 ± 1.00 12.89 ± 1.00 11.75 ± 0.99	
1022.3+1259	13 ± 0.9	6573.71	-29.67 ± 0.58	

EMSS	$v \sin i$ (km/s)	HJD (244+)	v_{rad} (km/s)	Comments
1022.6+1121	58 ± 9.7	6422.99	94.50 ± 0.90	binary RS
		6537.71	4.58 ± 0.97	
		6540.74	91.87 ± 0.81	
		6858.71	14.73 ± 1.10	
		6859.63	-18.63 ± 0.83	
		6859.92	-40.78 ± 1.05	
		6860.83	30.29 ± 1.08	
		6866.62	-39.73 ± 1.25	
		6869.69	-2.74 ± 0.96	
		6869.81	9.97 ± 1.74	
		6870.68	-27.40 ± 1.01	
		6871.75	46.37 ± 1.36	
		6873.60	-34.60 ± 1.10	
		6873.89	34.68 ± 1.24	
		6874.82	-39.52 ± 1.02	
1049.5-0849	...	6423.04	-65.60 ± 1.63	binary RS var line width
		6537.73	61.65 ± 1.31	
		6540.75	-1.43 ± 1.12	
		6858.75	-13.83 ± 2.59	
		6859.72	50.72 ± 1.98	
		6860.81	-1.54 ± 2.37	
		6865.77	-82.27 ± 1.98	
		6866.63	-86.95 ± 2.44	
		6870.72	-4.60 ± 1.98	
		6873.62	50.28 ± 2.13	
1050.2-0925	11 ± 1.2	6874.81	-72.78 ± 2.44	binary Me
		6426.96	2.81 ± 0.95	
		6537.74	52.26 ± 1.00	
		6540.76	1.47 ± 1.00	
1058.2+1220	...	...	...	too faint
1112.6+1311	< 10	6447.96	8.14 ± 1.26	

EMSS	$v \sin i$ (km/s)	HJD (244+)	v_{rad} (km/s)	Comments
1127.9-1502	21 ± 3.0	6447.97	56.48 ± 1.49	binary
		6537.75	-14.31 ± 1.50	RS, SB2
		6540.77	-59.53 ± 1.21	$P = 2.30$ d
		6574.71	-63.12 ± 1.52	$k = 102.8$ km/s
		6858.75	89.56 ± 1.93	$\gamma = 13.1$ km/s
		6859.75	-89.14 ± 1.43	
		6859.93	-63.49 ± 1.69	
		6860.82	118.55 ± 1.38	
		6865.78	70.71 ± 1.57	
		6869.71	82.64 ± 2.13	
		6869.82	103.95 ± 2.52	
		6870.72	-22.54 ± 2.13	
		6873.87	-27.11 ± 1.80	
		6874.84	91.32 ± 1.48	
		6896.64	-52.06 ± 1.63	
		6896.66	-46.51 ± 1.32	
		6896.72	-32.01 ± 1.29	
		6897.56	90.89 ± 2.15	
		6900.56	18.00 ± 1.06	
		6900.57	-12.08 ± 1.13	
1153.0+2344	< 10	6537.78	13.33 ± 1.00	
		7139.05	11.24 ± 0.64	
1208.6+3924	...	6573.72	-7.84 ± 1.37	binary
		6574.73	6.59 ± 1.49	RS or W
1211.8+1206	110 ± 10	...	...	binary, W
1213.9+3809	11 ± 1.8	6426.97	-37.32 ± 1.25	binary
		6569.72	-26.73 ± 1.34	RS
1215.1+6932	< 10	6423.05	5.32 ± 0.88	
		6537.84	5.41 ± 1.00	
		6540.79	5.91 ± 1.00	
		6427.02	6.15 ± 1.36	
1216.1+2818	21 ± 3.0	6540.78	-70.09 ± 2.06	binary
1222.5+2549	...	6573.72	-108.28 ± 1.85	RS
		6574.74	-101.00 ± 1.64	$P = 0.96$ d
		6427.00	-13.44 ± 0.89	
1224.7+7531	< 10	6537.86	-10.97 ± 1.00	
		6573.73	-11.46 ± 0.48	
1254.9+0142	22 ± 0.9	6574.76	-12.91 ± 0.49	
		6531.76	-12.33 ± 1.00	
		6447.99	-9.85 ± 0.71	
1255.3+3529a	< 10	6448.00	-4.02 ± 2.10	
1255.3+3529b	34 ± 8.5	6573.74	-11.87 ± 0.32	
1330.6-0811	< 10	6539.71	-11.37 ± 1.00	
1350.8+1810	...			

EMSS	$v \sin i$ (km/s)	HJD (244+)	v_{rad} (km/s)	Comments
1404.5+5502	22 ± 4.3	6998.67 7139.03	-15.54 ± 1.71 -17.56 ± 2.09	
1440.4+5213	70 ± 11.7	6573.76 6574.76	-15.26 ± 1.94 -5.66 ± 1.39	binary RS
1441.4+5222	11 ± 1.0	6427.06 6998.66	5.85 ± 0.98 5.58 ± 0.91	
1441.7+5208	< 10	6427.07 6448.07	-43.58 ± 0.69 -8.04 ± 0.44	binary
1457.0+2108	< 10	6448.06 6998.64	-32.76 ± 0.53 -31.70 ± 0.70	
1457.0+2226	20 ± 3.2	6997.67 7139.05	-142.23 ± 1.41 -13.08 ± 2.71	binary Me
1520.8-0625	35 ± 2.5	6573.77 6574.77	99.21 ± 0.70 90.09 ± 0.59	binary RS
1521.2+3027	3	6530.90	-103.22 ± 1.00	v_{rot} from BSC
1530.6+1342	21 ± 2.6	6537.89 6998.68	-120.02 ± 1.01 6.43 ± 1.59	binary Ke
1533.0+0919	30 ± 3.0	6569.73 6998.70	13.13 ± 0.91 -5.99 ± 1.21	binary Ke
1534.7+5448	...	...	...	
1548.8+1125	30 ± 3.0	5503.66 5504.66 5506.74 5507.65	$-20.51 \pm \sim 1$ -46.24 -70.99 -48.28	binary Ke; data from Silva <i>et al.</i> (1985)
1559.8+1753	< 10	6537.91 6997.80	-24.27 ± 1.00 -29.64 ± 0.67	binary
1559.9+4202	< 10	6569.79 6997.80	-4.76 ± 0.48 -5.15 ± 0.61	
1601.1+4119	< 10	6569.77 6572.93	-17.60 ± 0.88 -17.69 ± 0.80	
1615.0+3114	95 ± 10	6569.78 6572.94 6635.86 6636.64 6637.74 6638.65	90.83 ± 3.03 283.80 ± 3.45 -48.99 ± 2.89 93.99 ± 2.60 -219.66 ± 2.95 -111.18 ± 3.16	binary W
1621.5+2640	< 10	6997.74	-43.86 ± 0.69	
1634.8+2638	< 10	6573.82 6689.65	-22.74 ± 0.45 -22.27 ± 0.46	
1635.0+2651	34 ± 1.2	6573.83 6574.83 6688.65 6689.65	-21.80 ± 0.65 -22.57 ± 0.61 -24.19 ± 0.70 -22.53 ± 0.51	

EMSS	$v \sin i$ (km/s)	HJD (244+)	v_{rad} (km/s)	Comments
1640.1+5349	< 10	6537.97	0.00 ± 1.00	
		6700.62	-1.67 ± 1.20	
1640.6+6224	...	6573.86	73.43 ± 1.08	binary
		6574.85	41.47 ± 0.98	Be
		6688.67	-73.33 ± 1.17	
		6689.67	-88.24 ± 1.15	
1654.0+3515	95 ± 10	...	...	binary, W
1654.4-0415	< 10	6572.95	-2.59 ± 1.25	
		6700.60	-2.42 ± 1.67	
1704.3+5432	20 ± 1.0	6575.98	-17.17 ± 0.45	
		6347.59	-16.82 ± 1.00	
1709.2+5432	< 10	6573.87	2.35 ± 0.86	
		6688.68	1.91 ± 1.03	
		6689.68	1.63 ± 0.96	
1737.3+6847	< 10	6575.97	-37.61 ± 0.78	binary
1806.1+6944	100 ± 10	6569.80	309.40 ± 2.44	binary
		6572.97	-10.82 ± 2.87	W
		6700.64	-41.16 ± 2.61	
1810.4+6940	< 10	6538.01	-13.88 ± 1.00	
		6573.96	-13.93 ± 0.51	
		6688.70	-14.71 ± 0.54	
		6689.70	-14.58 ± 0.47	
1839.6+8002	< 10	6700.67	12.76 ± 1.33	
		6997.81	12.81 ± 1.15	
1849.2+7953	113	6573.98	11.91 ± 1.15	v_{rot} from BSC
		6688.71	8.85 ± 1.11	
		6689.73	9.06 ± 1.29	
2034.9+7532	29 ± 2.2	6997.85	-6.09 ± 0.83	
		6998.83	-8.48 ± 1.01	
2038.3-0046	100 ± 10	6573.98	148.34 ± 2.45	binary
		6688.73	-64.78 ± 2.31	W
		6689.74	109.21 ± 2.52	
2045.4+7523	60 ± 6.0	6997.85	-22.86 ± 1.38	
		6998.80	-21.67 ± 1.00	
2113.4+0517	< 10	6572.98	5.19 ± 0.59	binary
		6700.74	-14.23 ± 0.79	
		6998.87	2.37 ± 0.98	
2116.7-1042	60 ± 7.6	6572.98	-38.41 ± 1.56	binary
		6700.70	-81.31 ± 1.25	RS
2119.7+1655	100 ± 10	...	...	binary, W
2136.1-1509	< 10	6700.72	67.92 ± 0.86	
		6997.95	67.13 ± 0.76	
2148.3+1420	< 10	6422.63	-1.32 ± 0.76	binary
		6700.77	7.65 ± 0.83	

EMSS	$v \sin i$ (km/s)	HJD (244+)	v_{rad} (km/s)	Comments
2253.8+2036	37 ± 4.5	6329.83	-0.30 ± 1.23	
		6700.78	-1.47 ± 1.31	
2255.7+2039	18 ± 6.5	6997.89	-139.32 ± 2.81	
2332.5+0119	< 10	6329.85	-12.62 ± 1.03	
		6700.80	-11.00 ± 1.06	
2335.3+0305	< 10	6688.75	-14.68 ± 0.46	
		6689.74	-13.92 ± 0.41	
2346.9+1842a	< 10	6700.81	6.78 ± 1.12	
		6997.96	6.59 ± 0.95	
2346.9+1842b	21 ± 4.8	6700.82	17.86 ± 2.06	binary
		6997.96	10.02 ± 1.62	Me
2349.8-0112	50 ± 5.0	see	Table 5 on p. 125	FK
0326.7-2008	12 ± 0.8	6688.98	-55.46 ± 0.71	binary
		6689.96	33.07 ± 0.60	
0327.2-2416	< 10	6688.99	-66.80 ± 0.96	
0535.7-2839	...	...	...	
0535.8-2843	31	...	...	binary, BSC
0956.8-2225	15 ± 2.7	6540.77	62.74 ± 0.91	binary
		7139.06	-36.16 ± 1.16	
1110.8-2611	...	...	...	
1436.9-2628	...	6540.79	13.19 ± 1.00	binary
		6574.79	8.59 ± 0.83	SB2 ?
		6998.63	13.40 ± 0.87	
1552.0-2338	...	6537.92	-5.21 ± 1.15	
		6540.80	3.69 ± 0.85	
		6574.80	-0.18 ± 0.60	
		6635.65	-2.72 ± 1.08	
		6637.63	1.73 ± 1.07	
		6638.63	-1.22 ± 1.08	
		6639.63	2.59 ± 1.15	
		6640.63	-0.71 ± 0.98	
		6859.97	-2.71 ± 1.73	
		6860.98	-1.45 ± 1.63	
		6865.98	-1.91 ± 1.84	
		6924.76	1.34 ± 1.23	
		6931.70	2.71 ± 1.22	
1559.2-2232	...	...	...	
1751.0+7046	30 ± 2.1	see	Table 5 on p. 125	FK

Abbreviations used in Appendix C

BSC – Bright Star Catalogue (Hoffleit 1982)

FK – FK Comae candidate

γ – systemic velocity

k – semi-amplitude of velocity curve

Ke – dwarf K emission binary

Me – dwarf M emission binary

P – period of velocity curve

RS – RS CVn binary candidate

SB2 – double line spectroscopic binary

W – W UMa binary candidate

Appendix D

Chromospheric Line Strengths for the Dwarf K and M Flare Stars

EMSS	H α		Ca II K	
	f	EW	f	EW
	(10^{-14} ergs cm $^{-2}$ s $^{-1}$)	($\text{\AA}$)	(10^{-14} ergs cm $^{-2}$ s $^{-1}$)	($\text{\AA}$)
0205.5+1454a	...	...	...	...
0205.5+1454b	...	...	...	...
0232.5+2321	18.10	4.82	4.38	14.75
0233.8+0649	...	...	3.22	5.10
0234.4+0641	5.51	5.75	...	...
0241.7+1045a	67.50	3.03	82.80	9.68
0241.7+1045b	34.05	1.83	1.61	32.92
0401.7+2150a	3.64	5.27	2.66	19.84
0401.7+2150b	3.10	4.97	2.19	25.19
0429.4+1755	...	...	7.62	8.22
0443.9-0952	1.27	5.54	0.48	26.00
0502.9-1204	3.49	0.76	4.40	3.92
0815.3+7433	0.32	2.64	0.32	15.36
0816.2+7449	8.50	2.78	10.40	15.34
0907.0+0654	15.03	3.04	1.91	17.76
1050.2-0925	5.20	0.73	3.64	3.48
1058.2+1220	2.17	2.81	...	...
1112.6+1311	3.83	5.13	1.85	20.04
1216.1+2818	1.21	3.27	0.65	14.08
1224.7+7531	2.39	0.33	3.52	5.03
1255.3+3529a	94.40	2.40	37.90	9.30
1255.3+3529b	23.60	4.15	4.02	10.94
1404.5+5502	2.51	1.21	...	...
1441.4+5222	1.82	1.26	1.27	10.68
1457.0+2226	5.07	3.82	1.26	10.42
1530.6+1342	5.16	0.97	...	...
1533.0+0919	19.80	2.18	...	...
1640.1+5349	6.95	0.93	6.51	6.94
1654.4-0415	41.40	3.27	10.60	9.73
1839.6+8002	17.80	3.35	2.26	6.22
2255.7+2039	1.45	3.65	0.66	18.03
2332.5+0119	0.00	0.00	11.30	3.81
2346.9+1842a	10.40	1.17	8.26	5.34
2346.9+1842b	19.40	5.30	4.78	15.52

Appendix E

Optical Photometry of My EMSS Subsample

EMSS	V	B - V	U - B	(V - R) _{KC}	(R - I) _{KC}
0002.9+1602	8.57	0.44	-0.01	0.25	0.23
±	.024	.028	.049	.012	.005
0007.5+1051	5.51*	-0.07*	-0.24*	...	...
0009.9+1417	8.50	0.81	0.23	0.49	0.48
±	.024	.028	.049	.012	.005
0011.6+0840	11.54	1.03	0.54	0.41	0.54
±	.016	.011	.018	.008	.006
0031.9-0646	6.83†	...	...	...	...
0036.1+3309	10.33	0.69	0.12	0.39	0.39
±	.015	.009	.012	.007	.004
0039.2-0206	12.76	0.68	0.18	0.38	0.37
±	.016	.013	.022	.010	.011
0103.6+3206	10.14	0.51	-0.01	0.32	0.32
±	.015	.009	.011	.007	.004
0105.3+3144	6.25*	0.40*	-0.01*	...	...
0132.5+2101	10.76	0.59	0.06	0.35	0.33
±	.019	.008	.020	.010	.006
0134.4+2027	8.67	0.67	0.16	0.40	0.39
±	.019	.007	.019	.009	.005
0205.5+1454a	14.30	1.56	1.01	1.40	1.64
±	.029	.087	.540	.025	.012
0205.5+1454b	16.83†	1.56	1.01	1.40	1.64
0215.0+1813	7.29†	...	...	...	...
0232.5+2321	13.71	1.58	1.00	1.22	1.55
±	.018	.033	.151	.013	.007
0233.8+0649	13.13	1.25	1.08	0.80	0.76
±	.016	.018	.078	.010	.008
0234.4+0641	16.00	...	...	1.49	1.85
±	.500	...	...	.057	.160
0234.8-0210	10.38	0.76	0.39	0.43	0.36
±	.015	.009	.012	.007	.004
0234.2-0321	8.09	0.93	0.77	...	...
±	.019	.007	.020	...	...
0235.6+1631	13.98	0.64	0.08	0.42	0.32
±	.020	.024	.042	.019	.027
0241.7+1045a	11.06	1.38	1.16	0.92	0.97
±	.019	.010	.031	.010	.006

EMSS	V	B - V	U - B	(V - R) _{KC}	(R - I) _{KC}
0241.7+1045b	15.39	1.40	...	1.54	1.77
±	.056	.157	...	.058	.023
0244.9-0024	9.62	0.80	0.31	0.49	0.49
±	.015	.009	.011	.007	.003
0255.3+2018	12.34	1.25	1.41	0.85	0.75
±	.016	.012	.038	.008	.005
0257.4+0733	7.96	0.92	0.73	...	...
±	.019	.007	.020	...	...
0300.2-1528	8.44	0.87	0.83	0.46	0.40
±	.019	.007	.020	.009	.005
0307.5+1424	10.44	0.71	0.21	0.40	0.37
±	.015	.009	.012	.007	.004
0308.4+1413	11.38	0.63	0.11	0.39	0.39
±	.015	.010	.013	.008	.006
0315.8-1955	10.78	0.80	0.29	0.50	0.48
±	.015	.010	.013	.007	.005
0318.6-1926	10.26	1.08	0.88	0.64	0.58
±	.015	.009	.014	.007	.004
0333.1+0607	10.31	0.51	-0.01	0.32	0.32
±	.015	.009	.011	.007	.004
0337.6-0202	8.00†	...	...	...	...
0348.2-1404	10.65	0.81	0.35	0.49	0.45
±	.015	.009	.012	.007	.004
0356.9+1011	6.37*	0.42*	0.00*	...	0.22*
0401.7+2150a	14.95	1.64	...	1.24	1.45
±	.039	.125	...	.039	.021
0401.7+2150b	15.09	1.63	...	1.16	1.51
±	.044	.142	...	.045	.025
0402.4+2152	5.90*	0.62*	0.12*	...	...
0411.5+2327	8.05	0.66	0.18	...	...
±	.019	.007	.019	...	...
0429.4+1755	12.11	1.36	1.03	0.88	0.90
±	.015	.012	.027	.008	.005
0430.7+1754	6.25*	0.07*	-0.10*	...	...
0438.6+0213	10.63	0.85	0.30	0.52	0.53
±	.015	.009	.012	.007	.004
0443.8-1006	11.82	1.12	0.99	0.69	0.59
±	.016	.012	.027	.008	.006
0443.9-0952	16.39	1.47	...	1.61	1.63
±	.116	.341	...	.123	.052
0444.9-1000	15.80	...	...	0.87	1.20
±	...	...	...	.156	.084
0448.4+1058	6.76*	0.54*	0.05*	...	0.30*

EMSS	V	B - V	U - B	(V - R) _{KC}	(R - I) _{KC}
0451.7-0305	15.19	...	...	0.19	0.71
±	.070	...	...	.088	.080
0502.9-1204	12.97	1.57	1.29	1.16	1.46
±	.016	.019	.101	.009	.005
0505.0-0527	10.18	0.91	0.51	0.53	0.49
±	.015	.009	.012	.007	.004
0509.5-1607	13.68	1.07	...	0.64	0.64
±	.007	.010	...	.008	.008
0538.6-0949	8.61	0.64	0.12	0.38	0.36
±	.019	.007	.019	.009	.005
0657.5+7518	8.29	0.74	0.35	0.42	0.37
±	.019	.007	.019	.009	.005
0657.6+7529	7.26†	...	...	...	...
0730.3+6546	8.37	0.49	0.05	0.28	27.00
±	.019	.007	.019	.009	.005
0758.8+1411	10.22	0.49	0.03	0.30	0.29
±	.019	.008	.019	.009	.006
0801.7+2425	12.42	0.88	0.54	0.50	0.45
±	.016	.012	.019	.009	.007
0810.2+6305	9.36	0.65	0.12	0.37	0.35
±	.015	.009	.011	.007	.003
0815.3+7433	16.90	1.68	...	1.42	1.46
±	.116	.350	...	.123	.050
0816.2+7449	13.28	1.46	1.12	1.05	1.26
±	.017	.021	.098	.011	.007
0820.2+0201	8.79	0.61	0.06	0.36	0.34
±	.015	.008	.011	.007	.003
0824.0+2944	8.61	0.53	0.01	0.32	0.31
±	.015	.008	.011	.007	.003
0830.3+1126	7.93	0.68	0.29	...	...
±	.019	.007	.019	...	...
0830.7+2828	12.87	0.94	0.57	0.52	0.49
±	.017	.018	.036	.012	.013
0842.7+1900	6.82†	...	...	...	...
0851.2+2025	8.58	0.48	-0.04	0.28	0.27
±	.019	.007	.019	.009	.005
0907.0+0654	13.35	1.57	...	1.16	1.44
±	.008	.011	...	.009	.008
0920.6+7838	8.73	0.65	0.13	0.37	0.35
±	.015	.008	.011	.007	.003
0923.0-0610	7.89†	...	...	...	...
0924.3+3942	9.79	1.29	1.16	0.80	0.70
±	.015	.009	.013	.007	.003

EMSS	V	B - V	U - B	(V - R) _{KC}	(R - I) _{KC}
1019.8-1016	10.80	1.18	1.05	0.74	0.73
±	.015	.010	.018	.007	.004
1022.3+1259	8.24	0.37	0.14	0.22	0.19
±	.015	.008	.011	.007	.003
1022.6+1121	10.54	0.70	0.21	0.41	0.38
±	.015	.009	.012	.007	.004
1049.5-0849	11.17	0.78	0.29	0.40	0.56
±	.015	.010	.014	.008	.006
1050.2-0925	12.48	1.23	1.05	0.80	0.75
±	.016	.018	.062	.010	.008
1058.2+1220	15.96	1.82	...	1.48	1.87
±	.030	.069	...	.032	.031
1112.6+1311	15.14	1.73	...	1.20	1.65
±	.056	.060	...	.020	.012
1127.9-1502	9.38	0.62	0.09	0.35	0.34
±	.015	.009	.011	.007	.003
1153.0+2344	12.54	0.61	0.07	0.36	0.36
±	.016	.014	.019	.011	.012
1208.6+3924	8.02	0.41	-0.04	...	...
±	.019	.007	.019	...	...
1211.8+1206	9.12	0.77	0.34	0.44	0.39
±	.019	.007	.019	.009	.005
1213.9+3809	15.27	0.64	0.23	0.41	0.36
±	.042	.065	.145	.055	.084
1215.1+6932	9.80	1.01	0.80	0.61	0.56
±	.015	.009	.012	.007	.003
1216.1+2818	15.47	1.41	...	1.07	1.31
±	.038	.096	...	.040	.026
1222.5+2549	8.09	0.53	0.00	...	...
±	.019	.007	.019	...	...
1224.7+7531	12.33	1.36	1.24	0.85	0.83
±	.016	.016	.067	.009	.007
1254.9+0142	6.98†	...	...	...	...
1255.3+3529a	10.50	1.42	1.07	0.95	1.04
±	.019	.009	.022	.009	.005
1255.3+3529b	13.14	1.58	0.94	1.26	1.62
±	.020	.020	.094	.012	.007
1330.6-0811	7.20†	...	...	...	...
1350.8+1810	5.70*	0.84*	...	...	...
1404.5+5502	13.99	1.35	...	0.79	0.91
±	.038	.115	...	.038	.023
1440.4+5213	7.46†	...	...	...	...
1441.4+5222	14.03	1.53	1.10	0.95	1.05
±	.023	.040	.260	.018	.014

EMSS	V	B - V	U - B	(V - R) _{KC}	(R - I) _{KC}
1441.7+5208	8.20	0.64	0.10	0.35	0.34
±	.019	.007	.019	.009	.005
1457.0+2108	11.16	0.56	0.03	0.33	0.32
±	.019	.009	.020	.010	.007
1457.0+2226	14.59	1.48	0.52	1.02	1.20
±	.030	.071	.249	.029	.020
1520.8-0625	7.31†	...	...	...	...
1521.2+3027	5.61†	0.58*	0.04*	...	...
1530.6+1342	12.42	1.20	0.95	0.77	0.75
±	.020	.017	.055	.012	.009
1533.0+0919	11.68	1.14	0.83	0.65	0.64
±	.019	.012	.033	.010	.007
1534.7+5448	5.74*	...	...	...	...
1548.8+1125	12.78	1.13	0.98	0.63	0.58
±	.021	.023	.088	.014	.013
1559.8+1753	11.09	1.02	0.68	0.58	0.55
±	.019	.010	.025	.010	.006
1559.9+4202	10.28	0.92	0.70	0.49	0.43
±	.019	.008	.021	.009	.006
1601.1+4119	13.88	0.98	0.74	0.56	0.44
±	.027	.050	.235	.024	.020
1615.0+3114	12.55	0.57	0.15	0.40	0.40
±	.021	.017	.042	.013	.011
1621.5+2640	14.47	0.76	0.45	0.47	0.64
±	.036	.028	.055	.032	.044
1634.8+2638	7.98	0.32	-0.10	0.31	0.39
±	.032	.020	.035	.020	.010
1635.0+2651	8.01	0.50	0.03	0.30	0.25
±	.019	.006	.006	.007	.004
1640.1+5349	12.33	1.45	1.19	0.94	0.95
±	.020	.018	.130	.009	.005
1640.6+6224	7.23†	...	...	...	...
1654.0+3515	10.10	0.59	0.05	0.36	0.35
±	.019	.007	.007	.007	.004
1654.4-0415	12.29	1.86	1.67	1.27	1.48
±	.021	...	...	.011	.005
1704.3+5432	5.83*	...	...	...	...
1709.2+5432	8.83	1.15	1.03	0.68	0.57
±	.032	.020	.036	.020	.010
1737.3+6847	4.80*	0.43*	-0.01*	...	0.22*
1806.1+6944	10.48	0.61	0.08	0.34	0.33
±	.024	.028	.049	.012	.006
1810.4+6940	8.58	0.95	0.67	0.53	0.47
±	.024	.028	.049	.012	.005

EMSS	V	B - V	U - B	(V - R) _{KC}	(R - I) _{KC}
1839.6+8002	13.22	1.72	...	1.26	1.47
±	.027	.074	...	.018	.008
1849.2+7953	6.32*	...	...	...	...
2034.9+7532	11.58	0.87	0.25	0.49	0.51
±	.024	.029	.055	.013	.007
2038.3-0046	9.35	0.64	0.06	0.37	0.36
±	.024	.028	.049	.012	.005
2045.4+7523	8.92	0.47	-0.03	0.28	0.26
±	.024	.028	.030	.012	.005
2113.4+0517	12.76	0.84	0.40	0.44	0.52
±	.026	.038	.141	.018	.013
2116.7-1042	12.12	0.72	0.22	0.44	0.36
±	.026	.017	.141	.017	.012
2119.7+1655	11.73	0.57	0.06	0.34	0.30
±	.025	.031	.053	.014	.010
2136.1-1509	13.61	0.72	0.18	...	...
±	.013	.018	.141	...	...
2148.3+1420	14.40*	...	...	...	...
2253.8+2036	13.79	...	...	0.34	0.43
±	.036	...	...	.037	.034
2255.7+2039	15.80	1.36	...	1.02	1.17
±	.029	.040	...	.034	.012
2332.5+0119	9.53	1.38	1.15	0.72	0.84
±	.024	.028	.053	.012	.005
2335.3+0305	8.00†	...	...	...	...
2346.9+1842a	12.07	1.49	...	0.90	0.92
±	.025	.036	...	.013	.007
2346.9+1842b	14.08	...	...	1.23	1.25
±	.042	...	...	.040	.017
2349.8-0112	10.72	0.70	0.12	0.42	0.35
±	.020	.009	.013	.009	.008
0326.7-2008	8.90†	...	...	...	...
0327.2-2416	9.00†	...	...	...	...
0535.7-2839	7.17†	...	...	...	...
0535.8-2843	5.31*	0.46*	0.10*	...	...
0956.8-2225	9.20†	...	...	...	...
1110.8-2611	7.20†	...	...	...	...
1436.9-2628	9.19†	...	...	...	...
1552.0-2338	8.79†	...	...	...	...
1559.2-2232	8.00†	...	...	...	...
1751.0+7046	9.62	1.08	0.84	0.60	0.58
±	.019	.007	.013	.007	.004

*magnitudes come from the Bright Star Catalogue (Hoffleit 1982);
R – I magnitudes given are on the Johnson system

†magnitudes come from the SAO Star Catalogue

‡unresolved in photometry; individual V estimated from M_V and combined V

*V estimated from POSS

Appendix F

Adopted Parallaxes and Distance Estimates

EMSS	M_V	Method	E_{B-V}	Distance (pc)
0002.9+1602	3.14	p		121.9
0007.5+1051	0.60	t		95.9
0009.9+1417	5.95	p		32.4
0011.6+0840	7.00	p		80.9
0031.9-0646	2.90	p		61.1
0036.1+3309	4.70	p	0.055	124.1
0039.2-0206	8.40	p		74.5
0103.6+3206	3.30	p	0.060	214.8
0105.3+3144	2.80	p		49.0
0132.5+2101	4.40	p		187.1
0134.4+2027	5.10	p		51.8
0205.5+1454a	12.39	s		24.1
0205.5+1454b	14.92	s		24.1
0215.0+1813	2.40	s		95.1
0232.5+2321	12.48	p		17.6
0233.8+0649	8.10	p		101.4
0234.4+0641	14.77	p		17.6
0234.8-0210	5.70	p		86.3
0234.2-0321	6.50	p		20.9
0235.6+1631	4.50	s		787.1
0241.7+1045a	8.90	p		27.0
0241.7+1045b	14.90	s		14.1
0244.9-0024	5.90	p		55.5
0255.3+2018	-0.40	s		3531.8
0257.4+0733	0.20	s		356.5
0300.2-1528	5.50	p		38.7
0307.5+1424	5.20	p		111.7
0308.4+1413	3.80	s	0.105	285.8
0315.8-1955	6.50	p		71.8
0318.6-1926	7.20	p		40.9
0333.1+0607	3.30	s	0.050	235.5
0337.6-0202	5.70	s		28.8
0348.2-1404	6.10	p		81.3
0356.9+1011	3.50	p		37.5
0401.7+2150a	9.22	p	0.080	140.0
0401.7+2150b	9.36	p	0.080	140.0
0402.4+2152	5.09	t		14.5
0411.5+2327	5.05	p		39.8

EMSS	M_V	Method	E_{B-V}	Distance (pc)
0429.4+1755	5.69	p	0.130	160.0
0430.7+1754	-0.20	s	0.130	160.0
0438.6+0213	3.90	s	0.300	146.6
0443.8-1006	7.30	p		80.2
0443.9-0952	14.40	p		25.0
0444.9-1000	9.59	p		174.6
0448.4+1058	4.35	t		30.3
0451.7-0305	3.80	s		1896.7
0502.9-1204	11.84	p		16.8
0505.0-0527	6.50	p		54.5
0509.5-1607	7.10	p		207.0
0538.6-0949	3.80	s	0.120	77.6
0657.5+7518	3.00	s		114.3
0657.6+7529	6.00	s		17.9
0730.3+6546	3.30	s		103.3
0758.8+1411	3.60	s		210.9
0801.7+2425	6.20	p		175.4
0810.2+6305	4.85	p		79.8
0815.3+7433	10.80	s		166.0
0816.2+7449	10.54	p		35.3
0820.2+0201	4.80	p		63.1
0824.0+2944	3.80	s		91.6
0830.3+1126	0.40	s		313.5
0830.7+2828	6.60	p		179.5
0842.7+1900	2.70	s		66.7
0851.2+2025	3.60	s		99.1
0907.0+0654	11.76	p		20.8
0920.6+7838	4.90	p		58.4
0923.0-0610	1.50	s		189.7
0924.3+3942	8.06	t		22.2
1019.8-1016	7.50	p		45.7
1022.3+1259	1.20	s		255.9
1022.6+1121	5.30	p		111.7
1049.5-0849	5.30	s		149.3
1050.2-0925	8.70	s		57.0
1058.2+1220	14.81	p		17.0
1112.6+1311	10.80	s		73.8
1127.9-1502	4.50	s		94.6
1153.0+2344	4.80	p		353.2
1208.6+3924	3.60	p		76.2
1211.8+1206	5.60	p		50.6
1213.9+3809	2.90	s		2978.5
1215.1+6932	6.95	p		37.2
1216.1+2818	10.84	p		84.3

EMSS	M_V	Method	E_{B-V}	Distance (pc)
1222.5+2549	4.10	p		62.8
1224.7+7531	8.21	p		66.7
1254.9+0142	2.90	s		65.5
1255.3+3529a	8.91	t		20.8
1255.3+3529b	11.55	t		20.8
1330.6-0811	4.20	s		39.8
1350.8+1810	0.20	s		125.9
1404.5+5502	8.72	p		113.2
1440.4+5213	2.80	s		85.5
1441.4+5222	9.30	p		88.3
1441.7+5208	4.80	p		47.9
1457.0+2108	4.30	p		235.5
1457.0+2226	10.18	p		76.2
1520.8-0625	0.10	s		276.7
1521.2+3027	4.50	t		16.4
1530.6+1342	7.60	p		92.1
1533.0+0919	7.30	p		75.2
1534.7+5448	1.00	s		88.7
1548.8+1125	7.30	p		124.7
1559.8+1753	6.80	p		72.1
1559.9+4202	0.00	s		1137.6
1601.1+4119	6.40	p		313.3
1615.0+3114	4.50	p		407.4
1621.5+2640	5.72	s		562.3
1634.8+2638	3.40	p		80.7
1635.0+2651	3.59	p		76.6
1640.1+5349	8.88	p		49.0
1640.6+6224	0.60	s		211.8
1654.0+3515	4.60	p		125.9
1654.4-0415	12.40	t		9.5
1704.3+5432	4.14	t		21.7
1709.2+5432	7.32	t		20.0
1737.3+6847	3.07	t		22.2
1806.1+6944	4.55	p		153.5
1810.4+6940	6.44	p		26.8
1839.6+8002	12.31	p		15.2
1849.2+7953	2.20	s		66.7
2034.9+7532	4.15	p	0.350	182.8
2038.3-0046	3.80	s		128.8
2045.4+7523	3.80	p		105.7
2113.4+0517	6.15	p		209.9
2116.7-1042	5.30	p		231.2
2119.7+1655	3.30	s	0.110	412.7
2136.1-1509	4.50	s	0.120	553.1

EMSS	M_V	Method	E_{B-V}	Distance (pc)
2148.3+1420	6.50	s		380.2
2253.8+2036	8.10	s		137.4
2255.7+2039	10.06	p		140.6
2332.5+0119	8.38	t		17.0
2335.3+0305	3.30	s		87.1
2346.9+1842a	8.67	p		47.9
2346.9+1842b	11.28	p		36.6
2349.8-0112	0.10	s		1330.5
0326.7-2008	2.90	s		158.5
0327.2-2416	7.20	s		22.9
0535.7-2839	2.90	s		71.5
0535.8-2843	3.60	t		21.3
0956.8-2225	6.20	s		39.8
1110.8-2611	1.20	s		158.5
1436.9-2628	3.30	s		150.7
1552.0-2338	1.39	s		302.0
1559.2-2232	0.60	s		302.0
1751.0+7046	3.50	s		175.0

Key to Column (3)

p – photometric parallax

s – spectroscopic parallax

t – trigonometric parallax

Appendix G

Each Star's Contribution to the X-ray Luminosity Function

EMSS	$\log L_{bol}$ (ergs/s)	$\log L_x$ (ergs/s)	$\frac{1}{V_a}$ (10^{-3} pc^{-3})
0002.9+1602	34.23	29.77	0.0123
0007.5+1051	35.48	29.99	0.0178
0009.9+1417	33.15	29.54	0.0211
0011.6+0840	32.77	29.60	0.0171
0031.9-0646	34.32	29.69	0.0154
0036.1+3309	33.64	30.06	0.0041
0039.2-0206	32.38	28.88	0.1830
0103.6+3206	34.16	30.01	0.0061
0105.3+3144	34.36	28.96	0.1520
0132.5+2101	33.75	29.76	0.0127
0134.4+2027	33.47	29.50	0.0276
0205.5+1454a	31.53	28.71	0.3280
0205.5+1454b	30.92	28.10	2.6100
0215.0+1813	34.52	29.33	0.0465
0232.5+2321	31.51	28.43	0.8510
0233.8+0649	32.55	29.35	0.0390
0234.4+0641	30.95	27.82	6.6700
0234.8-0210	33.27	29.59	0.0176
0234.2-0321	33.01	28.30	1.3100
0235.6+1631	33.72	30.93	0.0003
0241.7+1045a	32.28	≤ 29.19	≥ 0.0656
0241.7+1045b	30.92	≤ 28.62	≥ 0.4420
0244.9-0024	33.20	29.63	0.0157
0255.3+2018	35.88	32.63	0.0000
0257.4+0733	35.54	30.66	0.0006
0300.2-1528	33.39	28.60	0.4720
0307.5+1424	33.46	29.22	0.0597
0308.4+1413	33.98	30.61	0.0013
0315.8-1955	33.14	29.67	0.0138
0318.6-1926	32.80	29.27	0.0513
0333.1+0607	34.17	29.99	0.0064
0337.6-0202	33.28	28.50	0.6530
0348.2-1404	33.13	29.67	0.0137
0356.9+1011	34.08	29.02	0.1260
0401.7+2150a	32.21	30.07	0.0040
0401.7+2150b	32.17	30.07	0.0040
0402.4+2152	33.48	28.56	0.5340
0411.5+2327	33.51	28.89	0.1770

EMSS	$\log L_{bol}$ (ergs/s)	$\log L_x$ (ergs/s)	$\frac{1}{V_e^2}$ (10^{-3} pc^{-3})
0429.4+1755	33.57	30.37	0.0016
0430.7+1754	35.68	30.93	0.0049
0438.6+0213	33.95	30.25	0.0031
0443.8-1006	32.78	29.08	0.0926
0443.9-0952	31.04	27.99	3.7900
0444.9-1000	32.20	29.77	0.0100
0448.4+1058	33.76	28.99	0.1400
0451.7-0305	33.98	32.48	0.0001
0502.9-1204	31.66	27.93	4.5700
0505.0-0527	32.97	30.38	0.0016
0509.5-1607	32.80	30.15	0.0031
0538.6-0949	33.98	29.31	0.0500
0657.5+7518	34.37	29.76	0.0103
0657.6+7529	33.19	28.74	0.2970
0730.3+6546	34.17	29.81	0.0108
0758.8+1411	34.05	30.02	0.0059
0801.7+2425	33.11	29.93	0.0060
0810.2+6305	33.58	29.06	0.1030
0815.3+7433	31.91	29.56	0.0194
0816.2+7449	31.97	28.64	0.4130
0820.2+0201	33.59	29.13	0.0803
0824.0+2944	33.98	29.43	0.0348
0830.3+1126	35.38	30.85	0.0005
0830.7+2828	32.97	29.73	0.0113
0842.7+1900	34.40	29.05	0.1130
0851.2+2025	34.05	29.46	0.0311
0907.0+0654	31.68	28.46	0.7900
0920.6+7838	33.56	29.19	0.0665
0923.0-0610	34.91	30.59	0.0024
0924.3+3942	32.60	28.43	0.8380
1019.8-1016	32.74	28.88	0.1860
1022.3+1259	35.02	30.26	0.0047
1022.6+1121	33.42	30.01	0.0047
1049.5-0849	33.42	30.07	0.0040
1050.2-0925	32.42	29.41	0.0319
1058.2+1220	30.94	27.96	4.1800
1112.6+1311	31.94	29.10	0.0905
1127.9-1502	33.72	29.97	0.0053
1153.0+2344	33.59	30.98	0.0003
1208.6+3924	34.04	28.97	0.1470
1211.8+1206	33.30	29.40	0.0327
1213.9+3809	34.36	31.99	0.0000
1215.1+6932	32.86	28.62	0.4440
1216.1+2818	31.90	28.98	0.1340

EMSS	$\log L_{bol}$ (ergs/s)	$\log L_x$ (ergs/s)	$\frac{1}{V_e}$ (10^{-3} pc^{-3})
1222.5+2549	33.86	29.81	0.0109
1224.7+7531	32.54	28.89	0.1800
1254.9+0142	34.32	29.15	0.0824
1255.3+3529a	32.37	≤ 29.04	≥ 0.1060
1255.3+3529b	31.73	≤ 29.04	≥ 0.1060
1330.6-0811	33.83	29.21	0.0608
1350.8+1810	35.54	30.02	0.0043
1404.5+5502	32.41	29.78	0.0096
1440.4+5213	34.36	29.24	0.0627
1441.4+5222	32.27	29.12	0.0826
1441.7+5208	33.60	29.06	0.1030
1457.0+2108	33.78	30.13	0.0044
1457.0+2226	32.06	29.52	0.0225
1520.8-0625	35.61	30.80	0.0006
1521.2+3027	33.70	27.93	4.8100
1530.6+1342	32.80	30.14	0.0031
1533.0+0919	32.79	29.57	0.0188
1534.7+5448	35.13	29.57	0.0281
1548.8+1125	32.79	30.03	0.0044
1559.8+1753	32.93	29.01	0.1180
1559.9+4202	35.62	31.37	0.0001
1601.1+4119	33.07	30.13	0.0033
1615.0+3114	33.71	30.39	0.0015
1621.5+2640	33.26	31.00	0.0003
1634.8+2638	34.11	29.96	0.0071
1635.0+2651	34.06	29.53	0.0249
1640.1+5349	32.37	28.94	0.1520
1640.6+6224	35.48	30.47	0.0081
1654.0+3515	33.67	29.53	0.0219
1654.4-0415	31.53	28.47	0.7270
1704.3+5432	33.84	29.12	0.0923
1709.2+5432	32.79	28.45	0.7900
1737.3+6847	34.26	29.04	0.1180
1806.1+6944	33.70	29.59	0.0209
1810.4+6940	33.04	28.83	0.2210
1839.6+8002	31.55	28.33	1.1600
1849.2+7953	34.60	29.16	0.0932
2034.9+7532	33.84	30.04	0.0056
2038.3-0046	33.98	30.27	0.0030
2045.4+7523	33.97	29.60	0.0201
2113.4+0517	33.28	30.10	0.0036
2116.7-1042	33.40	29.86	0.0076
2119.7+1655	34.17	30.54	0.0015
2136.1-1509	33.71	30.95	0.0003

EMSS	$\log L_{bol}$ (ergs/s)	$\log L_x$ (ergs/s)	$\frac{1}{V_d}$ (10^{-3} pc^{-3})
2148.3+1420	33.03	30.76	0.0005
2253.8+2036	32.60	30.00	0.0049
2255.7+2039	32.09	29.70	0.0125
2332.5+0119	32.50	28.58	0.5060
2335.3+0305	34.16	29.58	0.0217
2346.9+1842a	32.43	≤ 29.34	≥ 0.0398
2346.9+1842b	31.80	≤ 29.11	≥ 0.0855
2349.8-0112	35.51	32.04	0.0001

LIST OF REFERENCES

- Abt, H.A., and Levy, S.G. 1976, *Ap. J. Suppl.*, **30**, 273.
- Agrawal, P.C., Rao, A.R., and Sreekantan, B.V. 1986, *M.N.R.A.S.*, **219**, 225.
- Allen, R.G., Cromwell, R.H., Liebert, J.W., Macklin, R.H., and Stockman, H.S. 1984, *Instrumentation in Astronomy V*, ed. A. Boksenberg and D. Crawford, Proc. SPIE 445, p. 168.
- Ambruster, C., Snyder, W.A., and Wood, K.S. 1984, *Ap. J.*, **284**, 270.
- Antiochos, S.K., and Noci, G. 1986, *Ap. J.*, **301**, 440.
- Avni, Y., and Bahcall, J.N. 1980, *Ap. J.*, **235**, 694.
- Avni, Y., Soltan, A., Tananbaum, H., and Zamorani, G. 1980, *Ap. J.*, **238**, 800.
- Baars, J.W.M., Genzel, R., Pauliny-Toth, I.I.K., and Witzel, A. 1977, *Astr. Ap.*, **61**, 99.
- Benz, W., Mayor, M., and Mermilliod, J.C. 1984, *Astr. Ap.*, **138**, 93.
- Bessel, M.S. 1976, *P.A.S.P.*, **88**, 557.
- Böhm, K.-H., and Cassinelli, J. 1971, *Astr. Ap.*, **12**, 21.
- Böhm-Vitense, E. 1986, *Ap. J.*, **301**, 297.
- Boeshaar, P.C. 1976, Ph.D. Thesis, Ohio State University.
- Bookbinder, J.A. 1985, Ph.D. Thesis, Harvard University.
- Bopp, B.W. 1987, *Ap.J.*, **317**, 781.
- . 1982, in *Second Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, edited by M.S. Giampapa and L. Golub (SAO Special Report 392), p. 207.
- Bopp, B.W., Goodrich, B.D., Africano, J.L., Noah, P.V., Meredith, R.J., Palmer, L.H., and Quigley, R.J. 1984, *Ap. J.*, **285**, 202.
- Bopp, B.W., and Stencel, R.E. 1981, *Ap. J.*, **247**, L131.
- Bopp, B.W., and Fekel, F. 1977, *A.J.*, **82**, 490.
- Bouigue, R. 1973, *Trans. IAU*, **15A**, 409.

- Caillault, J.-P., Helfand, D.J., Nousek, J.A., and Takalo, L.O. 1986, *Ap. J.*, **304**, 318.
- Chaffee, F.C. 1974, *Ap.J.*, **189**, 427.
- Charles, P.A. 1983, in *Activity in Red Dwarf Stars*, ed. P.B. Byrne and M. Rodonò (Dordrecht:Reidel), p. 415.
- Clark, B.G. 1980, *Astr. Ap.*, **89**, 377.
- Coleman, G.D., and Worden, S.P. 1976, *Ap. J.*, **205**, 47.
- Collier, A.C. 1982, *Mon. Not. R. Astron. Soc.* **200**, 489.
- Cram, L.E. 1982, *Ap.J.*, **253**, 768.
- Cram, L.E., and Giampapa, M.S. 1987, *Ap.J.*, **323**, 316.
- Cram, L.E., and Mullan, D.J. 1979, *Ap. J.*, **234**, 579.
- Crudace, R.G., and Dupree, A.K. 1984, *Ap. J.*, **277**, 263.
- Dahn, C., Liebert, J., and Harrington, R. 1986, *A.J.*, **91**, 621.
- Downie, N.M., and Heath, R.W. 1965, *Basic Statistical Methods*, 2nd. ed. (New York:Harper and Row), p. 206.
- Duerbeck, H.W. 1984, *Ap. Sp. Sci.*, **99**, 363.
- Duncan, D.K. 1981, *Ap. J.*, **248**, 651.
- Dupree, A.K. 1983, in *Activity in Red Dwarf Stars*, ed. P.B. Byrne and M. Rodonò (Dordrecht:Reidel), p. 447.
- Eggen, O.J. 1985, *A.J.*, **90**, 74.
- _____. 1969, *P.A.S.P.*, **81**, 553.
- Favata, F., Rosner, R., Sciortino, S., and Vaiana, G.S. 1988, *Ap. J.*, **324**, 1010.
- Feigelson, E.D. 1984, in *Cool Stars, Stellar Systems, and the Sun*, ed. S. Baliunas and L. Hartmann (New York:Springer Verlag), p. 27.
- Florkowski, D.P., Johnston, K.J., Wade, C.M., and de Vegt, C. 1985, *A. J.*, **90**, 2381.
- Fontaine, G., Montmerle, T., and Michaud, G. 1982, *Ap. J.*, **257**, 695.

- Giacconi, R. *et al.* 1979, *Ap. J. (Letters)*, **234**, L1.
- Giampapa, M.S. 1988, in *Solar Radiative Output Variations*, NSF Publication, in press.
- _____. 1987, in *Fifth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, ed. J. Linsky and R. Stencel, in press.
- _____. 1985, *Ap.J.*, **299**, 781.
- Giampapa, M.S., Cram, L.E., and Wild, W.J. 1988, *Ap.J.*, submitted.
- Giampapa, M.S., Golub, L., Rosner, R., Vaiana, G.S., Linsky, J.L., and Worden, S.P. 1982, in *SAO Special Report No. 392*, p. 73.
- Giampapa, M.S., Worden, S.P., and Linsky, J.L. 1982, *Ap.J.*, **258**, 740.
- Gibson, D.M. 1985, In *Radio Stars*, edited by R. Hjellming and D. Gibson (Reidel, Dordrecht), p. 213.
- Gilman, P. 1983, *Ap. J. Suppl.*, **53**, 243.
- Gioia, I.M., Maccacaro, T., and Wolter, A. 1987, in *Observational Cosmology*, I.A.U. Symp. No. 124 (Dordrecht:Reidel), p. 593.
- Gioia, I.M., Maccacaro, T., Schild, R.E., Stocke, J.T., Liebert, J.W., Danziger, I.J., Kunth, D., and Lub, J. 1984, *Ap.J.*, **283**, 495.
- Gliese, W. 1982, *Astr. Ap. Suppl.*, **47**, 471.
- Gliese, W., and Jahreiß, H. 1979, *Astr. Ap. Suppl.*, **38**, 423.
- Golay, M. 1974, *Introduction to Astronomical Photometry* (Dordrecht:Reidel), p. 72.
- Golub, L. 1983, in *Activity in Red-Dwarf Stars*, ed. P.B. Byrne and M. Rodonò (Dordrecht:Reidel), p. 83.
- Gray, D.F. 1976, *The Observation and Analysis of Stellar Photospheres* (New York:John Wiley and Sons), p. 398.
- Griffiths, R.E. *et al.* 1983, *Ap. J.*, **269**, 375.
- Haisch, B.M. 1988, in *Fifth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun*, ed. J. Linsky and R. Stencel (New York:Springer Verlag), p. 269.
- _____. 1983, in *Activity in Red Dwarf Stars*, ed. P.B. Byrne and M. Rodonò (Dordrecht:Reidel), p. 255.

- Haisch, B.M., and Simon, T. 1982, *Ap. J.*, **263**, 252.
- Hall, D.S. 1976, in *Multiple Periodic Variable Stars*, IAU Colloq. No. 29, ed. W.S. Fitch (Dordrecht:Reidel), p. 287.
- Harnden, F.R., Fabricant, D.G., Harris, D.E., and Schwarz, J. 1984, *SAO Special Report No. 393*.
- Harris, H.C., and McClure, R.D. 1985, *Pub. Astr. Soc. Pac.*, **97**, 261.
- Harris, W.E., Fitzgerald, M.P., and Reed, B.C. 1981, *Pub. Astr. Soc. Pac.*, **93**, 507.
- Hartmann, L., Hewett, R., Stahler, S., and Mathieu, R. 1986, *Ap.J.*, **309**, 275.
- Hawkins, M.R.S. 1986, in *Astrophysics of Brown Dwarfs*, ed. M.C. Kafatos, R.S. Harrington, and S.P. Maran, p. 93.
- Hayes, D.S. 1978, in *The H-R Diagram*, I.A.U. Symp. No. 80, ed. A.G.D. Philip and D.S. Hayes (Dordrecht:Reidel), p. 63.
- Hoffleit, D. 1982, *The Bright Star Catalogue* (New Haven:Yale University Observatory).
- Hughes, V.A., and McLean, B.J. 1987, *Ap. J.*, **313**, 263.
- Iben, I. 1967, *Ann. Rev. Astr. Ap.*, **5**, 571.
- Jacoby, G.H., Hunter, D.A., and Christian, C.A. 1984, *Ap.J. Suppl.*, **56**, 257.
- Jahreiß, H., and Wielen, R. 1983, in *The Nearby Stars and the Stellar Luminosity Function*, IAU Colloquium No. 76, ed. by A.G.D. Philip and A.R. Upgren (Schenectady:Davis), p. 277.
- Johnson, H.M. 1986, *Ap.J.*, **303**, 470.
- Joy, A.H., and Abt, H.A. 1974, *Ap.J.Suppl.*, **28**, 1.
- Kahn, S.M., Wesemael, F., Liebert, J., Raymond, J.C., Steiner, J.E., and Shipman, H.L. 1984, *Ap. J.*, **278**, 255.
- Kuperus, M., Ionson, J.A., and Spicer, D.S. 1981, *Ann. Rev. Astr. Ap.*, **19**, 7.
- Landolt, A.U. 1983, *A. J.*, **88**, 439.
- Latham, D.W. 1985, in *Stellar Radial Velocities*, IAU Colloquium No. 88, ed. by A.G.D. Philip and D.W. Latham (Schenectady:Davis), p. 21.

- _____. 1982, in *Instrumentation for Astronomy with Large Optical Telescopes*, IAU Colloq. No. 67, ed. by C.M. Humphries (Dordrecht:Reidel), p. 259.
- Liebert, J., and Probst, R.G. 1987, *Ann. Rev. Astr. Ap.*, **25**, 473.
- Linsky, J.L. 1980, *Ann. Rev. Astr. Ap.*, **18**, 439.
- Linsky, J.L., Bornmann, P.L., Carpenter, K.G., Wing, R.F., Giampapa, M.S., Worden, S.P., and Hege, E.K. 1982, *Ap.J.*, **260**, 670.
- Lucy, L.B., and White, R.L. 1980, *Ap. J.*, **241**, 300.
- Maccacaro, T., Gioia, I.M., Wolter, A., and Zamorani, G. 1988, *Ap. J.*, **326**, in press.
- Maccacaro, T., Feigelson, E.D., Fener, M., Giacconi, R., Gioia, I.M., Griffiths, R.E., Murray, S.S., Zamorani, G., Stocke, J.T., and Liebert, J.W. 1982, *Ap.J.*, **253**, 504.
- Maggio, A., Sciortino, S., Vaiana, G.S., Majer, P., Bookbinder, J., Golub, L., Harnden, F.R., Jr., and Rosner, R. 1987, *Ap. J.*, **315**, 687.
- Mangenay, A., and Praderie, F. 1984, *Astr. Ap.*, **130**, 143.
- Marilli, E., and Catalano, S. 1984, *Astr. Ap.*, **133**, 57.
- Micela, G., Sciortino, S., Vaiana, G.S., Schmitt, J.H.M.M., Stern, R.A., Harnden, F.R., and Rosner, R. 1988, *Ap.J.*, **325**, in press.
- Mikami, T. 1978, *Pub. Astr. Soc. Japan*, **30**, 207.
- Morgan, W.W., Keenan, P.C., and Kellman, E. 1943, *An Atlas of Stellar Spectra* (Chicago:University of Chicago Press).
- Muchmore, D.O., and Böhm, K.-H. 1978, *Astr. Ap.*, **69**, 113.
- Mullan, D.J. 1985, In *Radio Stars*, edited by R. Hjellming and D. Gibson (Reidel:Dordrecht), p. 173.
- Mutel, R.L., and Lestrade, J.F. 1985, *A. J.*, **90**, 493.
- O'Connell, R.W. 1973, *A.J.*, **78**, 1074.
- Owen, F., Jones, T., and Gibson, D.M. 1976, *Ap. J.*, **210**, L27.
- Paerels, F., and Heise, J. 1988, *Ap. J.*, submitted.
- Pallavicini, R.P., Golub, L., Rosner, R., Vaiana, G.S., Ayres, T., and Linsky, J.L. 1981, *Ap.J.*, **248**, 279.

- Parker, E.N. 1979, *Cosmical Magnetic Fields* (Oxford:Clarendon Press).
- Petre, R., Shipman, H.L., and Canizares, C.R. 1986, *Ap. J.*, **304**, 356.
- Pettersen, B.R. 1983, in *Activity in Red Dwarf Stars*, ed. P.B. Byrne and M. Rodonò (Dordrecht:Reidel), p. 17.
- Piccinotti, G., Mushotzky, R.F., Boldt, E.A., Holt, S.S., Marshall, F.E., Serlemitsos, P.J., and Shafer, R.A. 1982, *Ap. J.*, **253**, 485.
- Popper, D.M. 1980, *Ann. Rev. Astr. Ap.*, **18**, 115.
- Pryor, C.P., Latham, D.W., and Hazen-Liller, M.L. 1986, submitted to *A. J.*,
- Ramsay, L.W., Nations, H.L., and Barden, S.C. 1981, *Ap. J.*, **251**, L101.
- Raymond, J.C., and Smith, B.W. 1977, *Ap.J.Supp.*, **35**, 419.
- Reid, I.N. 1987, *M.N.R.A.S.*, **225**, 873.
- Reid, I.N., and Gilmore, G.F. 1984, *M.N.R.A.S.*, **206**, 19.
- _____. 1982, *M.N.R.A.S.*, **201**, 73.
- Rosner, R., Golub, L., and Vaiana, G.S. 1985, *Ann. Rev. Astr. Ap.*, **23**, 415.
- Rosner, R., Avni, Y., Bookbinder, J., Giacconi, R., Golub, L., Harnden, F.R., Maxson, C.W., Topka, K., and Vaiana, G.S. 1981, *Ap. J.*, **249**, L5.
- Ruciński, S.M. 1984, *Astr. Ap.*, **132**, L9.
- Salpeter, E.E. 1955, *Ap. J.*, **121**, 161.
- Scalo, J.M. 1986, *Fundamentals of Cosmic Physics*, **11**, 1.
- Schmidt, M. 1968, *Ap.J.*, **151**, 393.
- Schmitt, J.H.M.M.², Harnden, F.R., Jr., Peres, G., Rosner, R., and Serio, S. 1985a, *Ap. J.*, **288**, 751.
- Schmitt, J.H.M.M., Golub, L., Harnden, F.R., Jr., Maxson, C.W., Rosner, R., and Vaiana, G.S. 1985b, *Ap. J.*, **290**, 307.
- Schrijver, C.J. 1983, *Astr. Ap.*, **127**, 289.
- Schrijver, C.J., and Rutten, R.G.M. 1987, *Astr. Ap.*, **177**, 143.
- Shipman, H.L. 1976, *Ap. J.*, **206**, L67.

- Silva, D., Gioia, I.M., Maccacaro, T., Mereghetti, S., Stocke, J.T. 1987, *A. J.*, in press.
- Silva, D., Liebert, J.W., Stocke, J.T., and Aaronson, M. 1985, *Pub. Astr. Soc. Pac.*, **97**, 1096.
- Simon, T., Herbig, G., and Boesgaard, A.M. 1985, *Ap. J.*, **293**, 551.
- Skumanich, A. 1986, *Ap. J.*, **309**, 858.
- _____. 1985, *Aust. J. Phys.*, **38**, 971.
- _____. 1972, *Ap. J.*, **171**, 565.
- Skumanich, A., and MacGregor, K. 1986, *Adv. Sp. Res.*, **6**, No. 8, 151.
- Skumanich, A., Young, A., Stauffer, J., and Bopp, B.W. 1984, *B.A.A.S.*, **16**, 940.
- Smith, R.C. 1983, *Observatory*, **103**, 29.
- Stauffer, J.R., Hartmann, L.W., and Latham, D.W. 1987, *Ap. J.*, **320**, L51.
- Stauffer, J.R., and Hartmann, L.W. 1986, *Ap.J.Suppl.*, **61**, 531.
- Stauffer, J.R., Hartmann, L.W., Soderblom, D., and Burnham, J. 1984, *Ap. J.*, **280**, 202.
- Stocke, J.T., Liebert, J.W., Gioia, I.M., Griffiths, R.E., Maccacaro, T., Danzinger, I.J., Kunth, D., and Lub, J. 1983, *Ap.J.*, **273**, 458.
- Swank, J.H. 1985, in *The Origin of Nonradiative Heating/Momentum in Hot Stars*, ed. A. Underhill and A. Michalitsianos, NASA Conference Publication 2358.
- Swank, J.H., and Johnson, H.M. 1982, *Ap.J.*, **259**, L67.
- Tonry, J., and Davis, M. 1979, *A.J.*, **84**, 1511.
- Turner, K.C. 1985, In *Radio Stars*, edited by R. Hjellming and D. Gibson (Reidel, Dordrecht), p. 283.
- Turnshek, D.E. 1981, M.S. Thesis, University of Arizona.
- Turnshek, D.E., Turnshek, D.A., Craine, E.R., and Boeshaar, P.C. 1985, *An Atlas of Digital Spectra of Cool Stars* (Tucson:Western Research Co.).
- Twarog, B.A. 1980, *Ap. J.*, **242**, 242.

- Ulmschneider, P. 1986, *Adv. Sp. Res.*, **6**, No. 8, 39.
- Upgren, A.R. 1963, *A. J.*, **68**, 194.
- Upgren, A.R., and Armandroff, T.E. 1981, *A. J.*, **86**, 1898.
- Vaiana, G.S. *et al.* 1981, *Ap. J.*, **245**, 163.
- Van 't Veer, F. 1975, *Astr. Ap.*, **40**, 167.
- Vilhu, O. 1984, *Astr. Ap.*, **133**, 117.
- Vilhu, O., and Walter, F.M. 1987, *Ap. J.*, **321**, 958.
- Walter, F.M., Brown, A., Mathieu, R.D., Myers, P.C., and Vbra, F.J. 1988, *A. J.*, submitted.
- Walter, F.M., and Basri, G.S. 1982, *Ap. J.*, **260**, 735.
- Walter, F.M., and Bowyer, S. 1981, *Ap. J.*, **245**, 671.
- Walter, F.M., Charles, P., and Bowyer, S. 1980, in *Cool Stars, Stellar Systems, and the Sun*, ed. A.K. Dupree (Smithsonian Astrophys. Obs. Special Rept. No. 389), p. 35.
- Webbink, R.F. 1976, *Ap. J.*, **209**, 829.
- Wielen, R., Jahreiß, H., and Kruger, R. 1983, in I.A.U. Colloq. 76 *The Nearby Stars and the Luminosity Function*, p. 163.
- Woolley, R., Epps, E., Penston, M., and Pocock, S. 1970, *Royal Obs. Ann.*, No. 5.
- Young, A., Sadjadi, S., and Harlan, E. 1987, *Ap.J.*, **314**, 272.
- Zarro, D.M., and Rodgers, A.W. 1983, *Ap. J. Suppl.*, **53**, 815.