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M DWARFS FROM THE *EINSTEIN* EXTENDED MEDIUM SENSITIVITY SURVEY[1]

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ABSTRACT

We present results from a complete sample of X-ray selected M dwarfs which were serendipitously detected in a subsample of the *Einstein Observatory* Extended Medium Sensitivity Survey (EMSS). The EMSS detected only M dwarfs of spectral type M5 and earlier, 93% of which were "emission" stars (i.e., type Me V), as well as two pre–main-sequence M stars. An X-ray luminosity function for early M dwarfs detected above our sensitivity limit of log $L_x = 27.8$ ergs s^{-1} is computed using the $1/V_a$ (sometimes called $1/V_{max}$) method (Avni and Bahcall; Schmidt). Comparison with the optical luminosity function of Wielen, Jahreiss, and Kruger suggests that some 42% of early M dwarfs emit X-rays at a level greater than log $L_x = 27.8$ ergs s^{-1}. This result agrees with the integral X-ray luminosity function calculated by Bookbinder from an optically selected sample. Arguments involving kinematics and stellar rotational velocities are used to estimate the age of these X-ray "bright" M dwarfs to be quite young ($\leq$1–3 $\times$ 10^9 yr).

We confirm the correlation of L_x with rotation and mass for the low-mass stars. Since the local space density of X-ray "bright" M dwarfs increases with decreasing mass, we infer a longer activity time scale for lower masses. M dwarfs later than M5 lie below our X-ray sensitivity. An upper limit of log $L_x = 27.45$ is put on their coronal emission. We argue against the existence of an X-ray luminous population of brown dwarfs.

We also present Hα and Ca II K line fluxes for most members of the sample and show that the Hα 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. Our results are consistent with the hypothesis that the chromosphere is heated by X-rays from the overlying corona.

Subject headings: Ca II emission — stars: chromospheres — stars: late-type — stars: X-rays

I. INTRODUCTION

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 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 cataloged stars which were either pointed targets or serendipitous detections (Pallavicini *et al.* 1981; Bookbinder 1985; Johnson 1986; Agrawal, Rao, and Sreekantan 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) catalog 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.[4]

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

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[4] Note that the supplement to an alternative catalog of Gliese and Jahreiss (1979) contains many new listings and updates earlier discoveries of known stars within about 20 pc ($\pi > 0\rlap{.}''045$) of the Sun. Moreover, a substantial number of late M dwarfs have been identified subsequently to both catalogs.

with higher tangential velocities will be represented in higher percentages than the low-velocity stars in the Woolley (or Gliese) catalog within a given absolute magnitude range. Second, 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). 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 catalog 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 catalog, consisting of stars within 10 pc of the Sun. This he argued to be relatively complete even down to the faintest M dwarfs. Second, he presented arguments based on statistical modeling 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. Our 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 *Einstein* Medium Sensitivity Survey (MSS; Gioia *et al.* 1984; Stocke *et al.* 1983; Maccacaro *et al.* 1982) and other parallel investigations (Caillault *et al.* 1986).

Second, we 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.

The data base from which this subset of M dwarfs was defined was the *Einstein* Extended Medium Sensitivity Survey (EMSS; Gioia, Maccacaro, and Wolter 1987). This contains an unbiased sample of 836 X-ray sources which were detected serendipitously by the *Einstein Observatory* Imaging Proportional Counter (IPC). The size of the sample has greatly increased over the previously published MSS (Gioia *et al.* 1984; Maccacaro *et al.* 1982) due to the inclusion of more IPC fields and the reprocessing of detected sources down to the 4 σ level. Optical identification of the MSS sources showed that about 25% of them were associated with stellar objects in our Galaxy (Gioia *et al.* 1984; Stocke *et al.* 1983), 6% being identified with M dwarfs.

Section II describes the data base for the EMSS M dwarf subsample. A luminosity function for X-ray emitting M dwarfs is presented and compared to optical luminosity functions in § III. The correlation of X-ray luminosity with stellar parameters is addressed in § IV. The nondetection of stars later than M5 is addressed in § V. In § VI, we analyse the chromospheric line fluxes and compare them with X-ray luminosity and rotation rates. A summary is given in § VII.

II. DATA BASE

For convenience of observation, we have defined a subsample of the EMSS above $\delta = -20°$ for which the X-ray data were reprocessed before 1985 August 15. This will not bias the sample, since the order in which the IPC frames were reprocessed was random with respect to M dwarfs. This subset includes 809 IPC fields covering 441 square degrees of the sky (56% of the total EMSS) and yielding 471 serendipitous detections. Over the past two years, we have obtained extensive optical spectroscopy and photometry of the 130 stars in this subsample. The Palomar Observatory Sky Survey (POSS) was used to locate optical counterparts within the X-ray position error box. Then, low-dispersion spectroscopy was obtained for as many of these objects as possible in order to identify the most likely X-ray source.

To date, 74% of the sources in this subsample have been positively identified with either galactic or extragalactic objects. For the purposes of the statistical arguments made below, it is necessary to know how many of the 26% of the sources which are unidentified could have stellar identifications. 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 mag generally have X-ray fluxes too faint to have been detected in the MSS. Of the 124 sources not yet identified, only six have objects in the error box at or brighter than 16th mag. The rest have objects fainter than 16th mag. We assume from the previous MSS work that they are extragalactic sources. The six sources associated with brighter objects, none of which are M stars, 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.

The observational data for the EMSS M stars consist of one soft X-ray (0.3–3.5 keV) flux, f_x, at the time of IPC detection and the following optical data for most members of the sample: (*a*) 5 Å resolution spectroscopy covering $\lambda\lambda$3600–7600; (*b*) 0.1 Å resolution echelle spectroscopy of the region around the Mg I *b* lines (5187 Å); (*c*) 0.1 or 0.9 Å resolution spectroscopy of the Hα and Ca II K line profiles; (*d*) *UBVRI* photometry.

The spectroscopy was taken at the Multiple Mirror Telescope (MMT) on Mount Hopkins, Arizona, with an echelle spectrograph (Chaffee 1974) and the MMT spectrograph (300 lines per mm and echellette gratings). The photometry was obtained either with the Catalina photometer at the Steward Observatory 1.5 m telescope on Mount Lemmon, Arizona, or with the automated filter photometer (AFP2) at the no. 2 0.9 m telescope on Kitt Peak, Arizona. Both filter sets were prescribed by Bessel (1976) with UBV on the Johnson system and RI on the Kron-Cousins system.

The 5 Å resolution spectra were used to assign spectral types to each member of the sample. The M-K classification extension to the M dwarfs (Boeshaar 1976) was utilized by comparison to standards and calculation of feature ratios found in the catalog of digital spectra of Turnshek *et al.* (1985) and Turnshek (1981). For this reason, we use the terminology "M V" and "Me V" throughout the paper. Following Joy and Abt (1974), the designation "Me" refers to the Balmer series in emission.

Distances to each star were calculated using trigonometric parallaxes when available. If not, photometric parallaxes were calculated using the M_V versus $(V-I)$ relation of Reid and Gilmore (1982). 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). After examining the spread in the M_V versus spectral type and $(V-I)$ relations, we estimate the errors in M_V to be 1.0 mag for spectroscopic parallaxes and 0.6 mag for photometric parallaxes. This source of error is much larger than the error in M_V introduced by the error in measuring $(V-I)$ or by misclassifying a star by one subtype. Errors in M_V for trigonometric parallaxes are usually on the order of 0.1 mag.

Two members of the sample (the multiple detection 1E0401.7+2150) are located in Taurus and 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. These two stars were assigned a distance (and corresponding M_V) of 140 pc based upon their projected spatial association with the Taurus dark cloud. As a result, if the f_x is split evenly between the two stars, they both have the greatest value of L_x (1.17×10^{30} ergs s^{-1}) of any star in the sample. Therefore, their contribution to the X-ray "bright" local space density is negligible compared to M dwarfs. They 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. One possible exception is 1E0444.9−1000. It is the only star in the sample which shows no indication of strong chromospheric activity (see § VI). 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 we 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.

The soft X-ray flux, f_x, was derived from corrected IPC counts per s by assuming a thermal spectral distribution with metallic absorption lines (Raymond and Smith 1977). *Einstein Observatory* Solid State Spectrometer spectra (Swank 1985; Swank and Johnson 1982), as well as temperature fits made of IPC data having sufficient counts for a spectral analysis by Bookbinder (1985), show that M dwarf coronae are well characterized by two temperature components. The cooler component ranges from log T of 5.9 to 6.5 and the hotter component from log T of 7.0 to 7.3. The counts-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} per count, is well established (Vaiana *et al.* 1981). The soft X-ray luminosity, L_x, was computed for each star assuming isotropic emission.

Furthermore, there were five EMSS sources which had two 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 (see § IV). 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 0.1 Å resolution echelle spectroscopy centered at 5187 Å was used to measure rotation rates ($v \sin i$) and radial velocities for each star. Both quantities were measured using the cross-correlation technique of Tonry and Davis (1979) with the templates described by Latham (1985). The manner in which we measure the rotation rate is identical to that described by Hartman *et al.* (1986). The echelle resolution limits the ability to measure rotation below 10 km s^{-1}. Zero-point corrections to the radial velocities were determined by observing IAU standards (Bouigue 1973) as well as the dawn and dusk skies.

Integrated line fluxes for the Hα 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, Hunter, and Christian (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 Hα and Ca II K. The line profiles were then integrated over wavelength and, for Hα 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.

These data for the 31 M dwarfs from the EMSS subsample described above are tabulated in Tables 1 and 2. In Table 1, column (1) gives the EMSS X-ray source designation, while column (2) lists names from other catalogs. The M-K spectral type is in column (3). Columns (4) and (5) contain the apparent and the derived absolute V magnitudes. The letter after M_V describes how it was computed ("t" = trigonometric parallax; "p" = photometric parallax; "s" = spectroscopic parallax; "k" = distance assigned from kinematic properties, in this particular instance, association with the Taurus dark cloud). Columns (6)–(9) contain the $UBVRI$ colors.

Table 2 gives the results of the coronal, chromospheric, and kinematic observations. Column (1) lists the EMSS X-ray source designation. Columns (2), (3), and (4) contain, respectively, the X-ray, Hα, and Ca II K line fluxes in ergs s^{-1} cm^{-2}. In columns (5) and (6), we provide the emission equivalent widths of the Hα and Ca II K lines. Although this quantity is not used in our analyses below, we recognize the value of making this more direct measurement available to the reader. Projected rotational velocity is found in column (7). Finally, column (8) gives the radial velocity for those stars with more than two observations. If v_{rad} varies, the word "binary" is entered.

A paper containing the entire EMSS catalog is in prep-

TABLE 1

X-Ray Selected Sample of M Dwarfs from the Extended Medium Sensitivity Survey

Source Name (1)	Other (2)	Spectral Type (3)	V (4)	M_V (5)	$B-V$ (6)	$U-B$ (7)	$(V-R)_{KC}$ (8)	$(R-I)_{KC}$ (9)	Notes (10)
1E0205.5+1454a	...	M4e	14.30	12.39 s	1.56	1.01	1.40	1.64	1
1E0205.5+1454b	...	M5e	16.83	14.92 s	1.56	1.01	1.40	1.64	1
1E0232.5+2321	...	M3e	13.71	12.48 p	1.58	1.00	1.22	1.55	
1E0234.4+0641	...	M5e	16.00	14.77 p	...	...	1.49	1.85	
1E0241.7+1045a	...	M0e	11.06	8.90 p	1.38	1.16	0.92	0.97	2
1E0241.7+1045b	...	M5e	15.39	14.66 p	1.40	...	1.54	1.77	2
1E0401.7+2150a	...	M3e	14.95	9.22 k	1.64	...	1.24	1.45	3
1E0401.7+2150b	...	M3e	15.09	9.36 k	1.63	...	1.16	1.51	3
1E0443.9−0952	...	M5e	16.39	14.40 p	1.47	...	1.61	1.63	
1E0444.9−1000	...	M0	15.80	9.59 p	...	...	0.87	1.20	4
1E0502.9−1204	LP 716–35	M4e	12.97	11.84 p	1.57	1.29	1.16	1.46	
1E0815.3+7433	...	M3e	16.90	10.80 s	1.68	...	1.42	1.46	5
1E0816.2+7449	...	M2e	13.28	10.54 p	1.46	1.12	1.05	1.26	
1E0907.0+0654	...	M4e	13.35	11.76 p	1.57	...	1.16	1.44	
1E1050.2−0925	...	M0e	12.48	8.70 s	1.23	1.05	0.80	0.75	6
1E1058.2+1220	...	M5e	15.96	14.81 p	1.82	...	1.48	1.87	
1E1112.6+1311	...	M3e	15.14	10.80 s	1.73	...	1.20	1.65	5
1E1216.1+2818	...	M2e	15.47	10.84 p	1.41	...	1.07	1.31	
1E1224.7+7531	...	M0e	12.33	8.21 p	1.36	1.24	0.85	0.83	
1E1255.3+3529a	GL 490A	M0e	10.50	8.91 t	1.42	1.07	0.95	1.04	
1E1255.3+3529b	GL 490B	M4e	13.14	11.55 t	1.58	0.94	1.26	1.62	
1E1404.5+5502	...	M0e	13.99	8.72 p	1.35	...	0.79	0.91	
1E1441.4+5222	...	M1.5e	14.03	9.30 p	1.53	1.10	0.95	1.05	
1E1457.0+2226	...	M2e	14.59	10.18 p	1.48	0.52	1.02	1.20	
1E1640.1+5349	...	M0e	12.33	8.88 p	1.45	1.19	0.94	0.95	
1E1654.4−0415	LHS 3255	M4e	12.29	12.40 t	1.86	1.67	1.27	1.48	
1E1839.6+8002	LP 25–2	M4e	13.22	12.31 p	1.72	...	1.26	1.47	
1E2255.7+2039	...	M3e	15.80	10.06 p	1.36	...	1.02	1.17	
1E2332.5+0119	GL 900	M1	9.53	8.38 t	1.38	1.15	0.72	0.84	
1E2346.9+1842a	...	M0e	12.07	8.67 p	1.49	...	0.90	0.92	
1E2346.9+1842b	...	M3e	14.08	11.26 p	...	...	1.23	1.25	7

Notes.—(1) Unresolved in photometry; individual V estimated from M_V and combined V; (2) a and b over 20″ apart; (3) PMS close pair; resolved in both photometry and spectroscopy; (4) V estimated from POSS since photometry taken near full Moon; possible PMS; (5) $V-I$ is too red for spectral type; photometry has very low SNR due to faintness of object; (6) colors are too blue for spectral type; star is binary; possible contamination; (7) a and b over 20″ apart; probable error in R magnitude for b.

aration. Coordinates and finding charts for the M dwarfs listed in Table 1 are available from the first author upon request.

III. 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 M dwarfs. We emphasize that the central region of each IPC frame (circle having a 5′ radius together with the target object) associated with a pointed observation was excluded from the sky coverage in order to avoid selection biases (Maccacaro *et al.* 1982). 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 our 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, we 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 height is 350 pc (Upgren 1963). Then, each star's contribution to the luminosity function is just $1/V_a'$.

Because our sample is purely X-ray selected, we can legitimately calculate such a function. However, the X-ray selection also limits this function to those stars with large L_x values. In addition, our sample is more sensitive to transient X-ray activity (i.e., detection of stars in flare) than optically selected samples. 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, Rao, and Sreekantan 1986; Ambruster, Snyder, and Wood 1984; Haisch 1983). So, in a sense, all of our derived L_x values might be treated as maxima. However, we believe this bias to be minimal in light of the fact that the log mean L_x of the EMSS M dwarfs is 29.16, which is a factor of 2 greater than the log mean L_x = 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 M dwarf, as well as its contribution to the luminosity function ($1/V_a'$), is listed in Table 3. In addition, Table 3 gives the value of L_{bol} for each star which will be used in subsequent analyses. The bolometric corrections were computed from the relation given by Pettersen (1983). Figure 1 represents the "bright" end of the M dwarf X-ray luminosity function (log $L_x > 27.8$ ergs s^{-1}). The X-ray

TABLE 2

CORONAL, CHROMOSPHERIC, AND KINEMATIC PROPERTIES OF THE EMSS M DWARF SUBSAMPLE

Source Name	f_x	$f_{H\alpha}$	$f_{Ca\ II\ K}$	EW(Hα)	EW(Ca II K)	$v \sin i$	v_{rad}
	(ergs s^{-1} cm^2)			(Å)		(km s^{-1})	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
0205.5+1454a	7.36E−13	...	...	...	...	≤10	13.44
0205.5+1454b	1.80E−13	...	...	...	...	≤10	12.69
0232.5+2321	7.19E−13	1.81E−13	4.38E−14	4.82	14.75	14	−12.04
0234.4+0641	1.79E−13	5.51E−14	...	5.75	...	...	...
0241.7+1045a	≤1.78E−12	6.75E−13	8.28E−13	3.03	9.68	28	binary
0241.7+1045b	≤1.78E−12	3.41E−13	1.61E−14	1.83	32.92	17	11.89
0401.7+2150a	4.99E−13	3.64E−14	2.66E−14	5.27	19.84	12	...
0401.7+2150b	4.99E−13	3.1E−14	2.19E−14	4.97	25.19	...	...
0443.9−0952	1.30E−13	1.27E−14	4.80E−15	5.54	26.00	...	...
0444.9−1000	1.61E−13	...	...	...	...	...	...
0502.9−1204	2.53E−13	3.49E−14	4.40E−14	0.76	3.92	≤10	2.08
0815.3+7433	1.11E−13	3.17E−15	3.15E−15	2.64	15.36	...	...
0816.2+7449	2.93E−13	8.50E−14	1.04E−13	2.78	15.34	≤10	8.97
0907.0+0654	5.53E−13	1.50E−13	...	3.04	17.76	≤10	...
1050.2−0925	6.61E−13	5.20E−14	3.64E−14	0.73	3.48	11	binary
1058.2+1220	2.64E−13	2.17E−14	...	2.81	...	...	...
1112.6+1311	1.91E−13	3.83E−14	1.85E−14	5.13	20.04	≤10	...
1216.1+2818	1.11E−13	1.21E−14	6.49E−15	3.27	14.08	21	...
1224.7+7531	1.45E−13	2.39E−14	3.52E−14	0.33	5.03	≤10	−12.20
1255.3+3529a	≤2.13E−12	9.44E−13	3.79E−13	2.40	9.30	≤10	−9.50
1255.3+3529b	≤2.13E−12	2.36E−13	4.02E−14	4.15	10.94	34	−3.80
1404.5+5502	3.94E−13	2.51E−14	...	1.21	...	22	−16.45
1441.4+5222	1.41E−13	1.82E−14	1.27E−14	1.26	10.68	11	5.72
1457.0+2226	4.73E−13	5.07E−14	1.26E−14	3.82	10.42	20	binary
1640.1+5349	3.02E−13	6.95E−14	6.51E−14	0.93	6.94	≤10	−0.83
1654.4−0415	2.74E−12	4.14E−13	1.06E−13	3.27	9.73	≤10	−2.50
1839.6+8002	7.80E−13	1.78E−13	2.26E−14	3.35	6.22	≤10	12.79
2255.7+2039	2.12E−13	1.45E−14	6.57E−15	3.65	18.03	18	...
2332.5+0119	1.11E−12	0.00E+00	1.13E−13	00.00	3.81	≤10	−11.81
2346.9+1842a	≤8.04E−13	1.04E−13	8.26E−14	1.17	5.34	≤10	6.68
2346.9+1842b	≤8.04E−13	1.9E−13	4.78E−14	5.30	15.52	21	binary

luminosities are binned into intervals of 0.4 in the log of L_x (which corresponds to the size of an optical magnitude.) Error bars represent Poisson errors. As for the six stars with maximum values of L_x, their minimum values of $1/V_a'$ are included since we 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 Figure 1 represent lower limits. There are no stars of spectral type later than M5 represented in this distribution.

To further test the uniformity of the sample, we have calculated $\langle V_e'/V_a' \rangle$ (as defined by Avni and Bahcall 1980). The six 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 uniform sample of 25, one would expect a result of 0.5 ± 0.06. We calculate $\langle V_e'/V_a' \rangle = 0.52$. The quantity $\langle V/V_{max} \rangle$ (as defined by Schmidt 1968) only takes into account the survey sensitivity in the field where an object was detected. The value of $\langle V/V_{max} \rangle$, without the correction for Galactic scale height, is 0.49. This indicates that the EMSS M star sample is indeed uniform and isotropic, that the Galactic scale height correction is negligible, and that our estimate of V_a is reasonable. This is not surprising since every member of the sample is within 160 pc of the Sun. Compared to a disk scale height of 350 pc, the stars within this volume should appear to be isotropically distributed.

It is useful to compare these results with the known distribution of M stars in the solar neighborhood from optical data. For early M stars, we use the luminosity function of Wielen, Jahreiss, and Kruger (1983). The local space density for stars in the absolute magnitude interval $8.5 < M_V < 15.5$ (i.e., M0–M5 dwarfs) is 80.7 ± 11.1 per 10^3 pc^3. By summing the data in Figure 1, one finds the local space density of stars in the same M_V range which have X-ray luminosities greater than log $L_x = 27.8$. This number is 34.1 ± 12.2 per 10^3 pc^3. The large error is due to the fact that the stars at the low-luminosity end, which contribute most to this value, are few in number. Therefore, the ratio of early M dwarfs with log $L_x > 27.8$ to all early M dwarfs is at least 0.42 ± 0.16. Despite the substantial errors on this result, there is good agreement with the findings of Bookbinder (1985). For his optically selected, volume-limited sample, he found the fraction of young disk M dwarfs out to 25 pc with log $L_x > 27.8$ ergs s^{-1} to be ~ 0.40. His sample, the McCormick subset of the Woolley catalog, is effectively color-selected and, hence, largely free of kinematical bias.

It is useful to note the fraction of X-ray "bright" M dwarfs as a function of M_V (or mass). This is shown in Figure 2. 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 fact, the Me dwarfs. Figure 2 also reveals a dependence of L_x upon mass, which will be discussed in the next section. The turnover of the higher mass curve at low X-ray luminosity (i.e., the lack of M0–M3 detections within 25 pc of the Sun) can be attributed to incompleteness. Since the local space density of all early-M dwarfs is less than that of all

TABLE 3

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

Source Name	log L_{bol} (ergs s^{-1})	log L_x (ergs s^{-1})	$1/V_a'$ (10^{-3} pc^{-3})
1E0205.5+1454a	31.53	28.71	0.328
1E0205.5+1454b	30.92	28.10	2.610
1E0232.5+2321	31.51	28.43	0.851
1E0234.4+0641	30.95	27.82	6.670
1E0241.7+1045a	32.37	≤29.19	≥0.066
1E0241.7+1045b	30.98	≤28.62	≥0.442
1E0401.7+2150a	32.29	30.07	0.004
1E0401.7+2150b	32.26	30.07	0.004
1E0443.9−0952	31.04	27.99	3.790
1E0444.9−1000	32.20	29.77	0.010
1E0502.9−1204	31.66	27.93	4.570
1E0815.3+7433	31.91	29.56	0.019
1E0816.2+7449	31.97	28.64	0.413
1E0907.0+0654	31.68	28.46	0.790
1E1050.2−0925	32.42	29.41	0.032
1E1058.2+1220	30.94	27.96	4.180
1E1112.6+1311	31.91	29.10	0.091
1E1216.1+2818	31.90	28.98	0.134
1E1224.7+7531	32.54	28.89	0.180
1E1255.3+3529a	32.37	≤29.05	≥0.106
1E1255.3+3529b	31.73	≤29.05	≥0.106
1E1405.5+5502	32.41	29.78	0.010
1E1441.4+5222	32.27	29.12	0.083
1E1457.0+2226	32.06	29.52	0.023
1E1640.1+5349	32.37	28.94	0.152
1E1654.4−0415	31.53	28.47	0.727
1E1839.6+8002	31.55	28.33	1.160
1E2255.7+2039	32.09	29.70	0.013
1E2332.5+0119	32.50	28.58	0.506
1E2346.9+1842a	32.43	≤29.34	≥0.040
1E2346.9+1842b	31.80	≤29.11	≥0.086

mid-M dwarfs, the volume of space sampled by the EMSS at $L_x = 10^{28}$ ergs s^{-1}, while sufficient to include a number of the latter, is insufficient to include many of the former.

As for the kinematics of our sample, only five members appear in the proper motion catalogs. We calculate their space motions to be young disk using the criteria of Eggen (1969) and from the fact that four out of five have $|W| < 15$ km s^{-1}. Young, Sadjadi, and Harlan (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, we do not have sufficient coverage to determine the binary frequency for the entire sample. Of the 20 stars with such coverage, only four 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.

We note that the fraction of astrophysical binaries discovered in our X-ray selected sample is significantly lower than that in the optically selected sample of Young, Sadjadi, and Harlan (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, we must caution that the binarity status of a third of our sample is still in question. With such a small

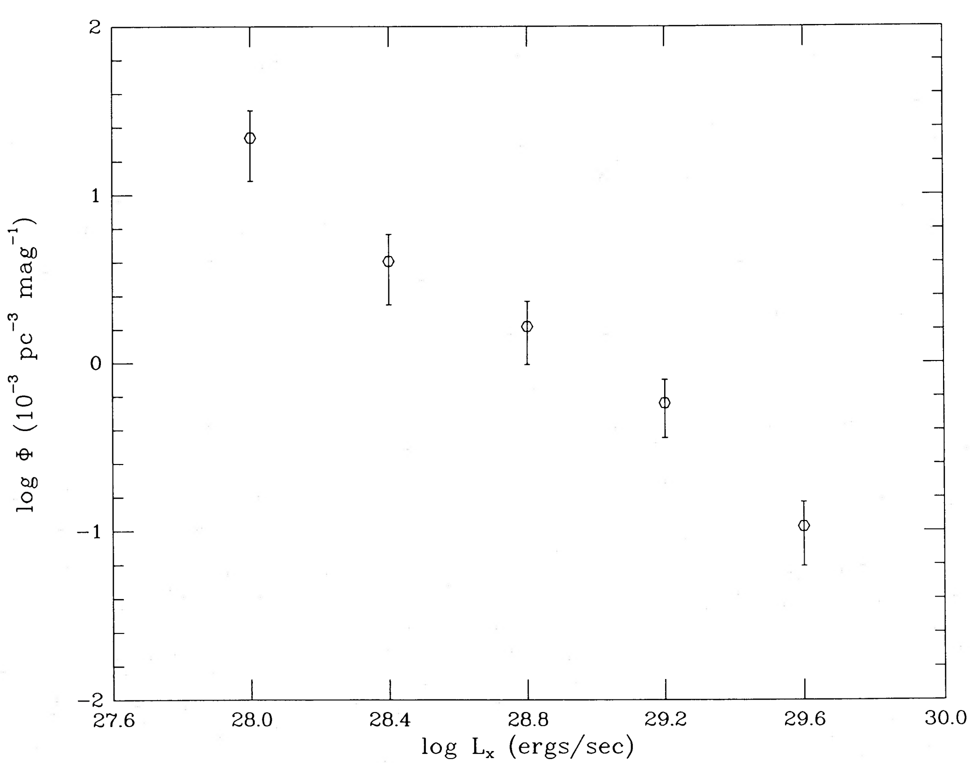


Fig. 1.—X-ray luminosity function for dwarfs with $8.5 < M_V < 15.5$ (i.e., M0 through M5) and log $L_x > 27.8$ ergs s^{-1}. The data are binned into intervals of 0.4 in logarithm space (1 mag). The error bars represent Poisson errors.

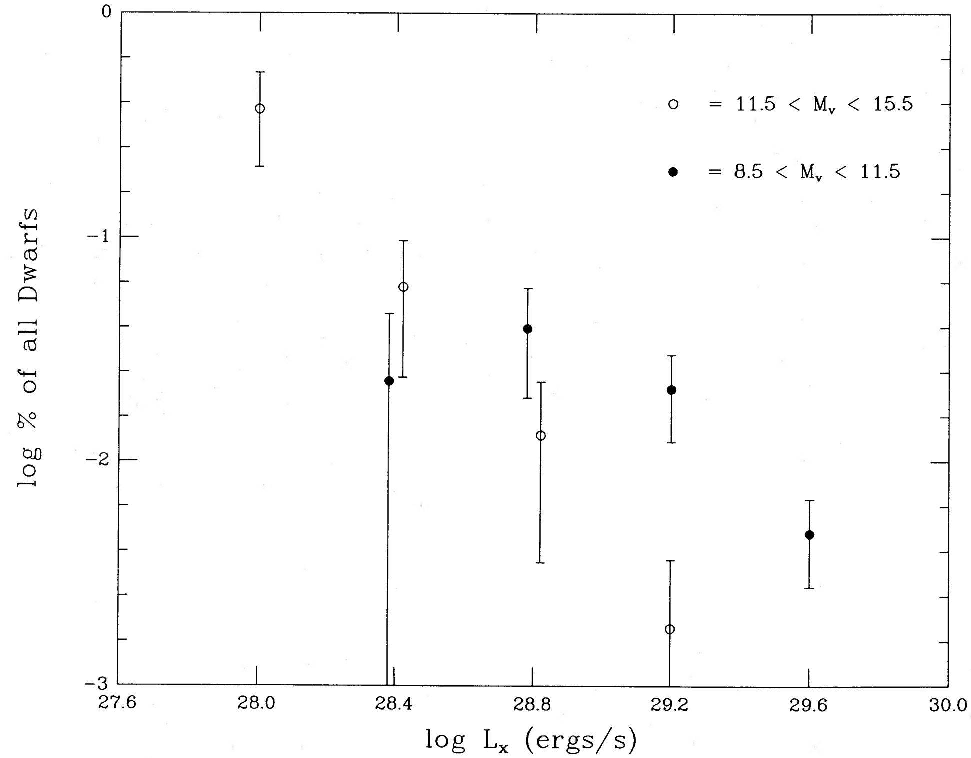


FIG. 2.—Fraction of all local M dwarfs in two absolute visual magnitude bins (which correspond to M0–M3 and M4–M5) as a function of soft X-ray luminosity

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 $\tau \leq 5 \times 10^8$ yr, the calibrations of Jahreiss and Wielen (1983) indicate that stars which display young disk kinematics have ages $\tau \leq 3 \times 10^9$ yr. Most authors avoid relating kinematic data directly to stellar age, opting instead to use some indirect indicator of age, such as Ca II H and K emission strength. This is due to the fact that, besides the Sun, no age calibrators exist beyond 10^9 yr. 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 ($\tau \sim 7 \times 10^7$ yr) rotate with $v \sin i \sim 50$ km s^{-1}, while the $v \sin i$ measurements of M dwarfs in the Hyades ($\tau \sim 6 \times 10^8$ yr) fall between 10 and 20 km s^{-1}. About half of our sample falls above the detection limit of 10 km s^{-1}. The largest $v \sin i$ measured is 34 km s^{-1}, while most fall between 20 and 30 km s^{-1}. 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., $\tau \leq 1$–3×10^9 yr).

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 $\geq 10^9$ yr. Our data indicate specifically that 0.42 ± 0.16 of all local M0–M5 dwarfs have high ($> 10^{27.8}$ ergs s^{-1}) X-ray luminosities. Whether this also means that this same fraction of all local M dwarfs were formed in the last 10^9 yr or the last 3×10^9 yr cannot be determined for the reasons given above. Of particular concern is that half of the sample for which $v \sin i < 10$ km s^{-1} (and, presumably, $v_{rot} > 5$ km s^{-1}; 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 traveling 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 $\leq 10^9$ yr. However, in the next section, we suggest a more plausible explanation for the high fraction of X-ray bright M dwarfs.

IV. 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. Our data confirms that this parameter is stellar rotation.

We produce a plot similar to that of Ruciński (1984) with

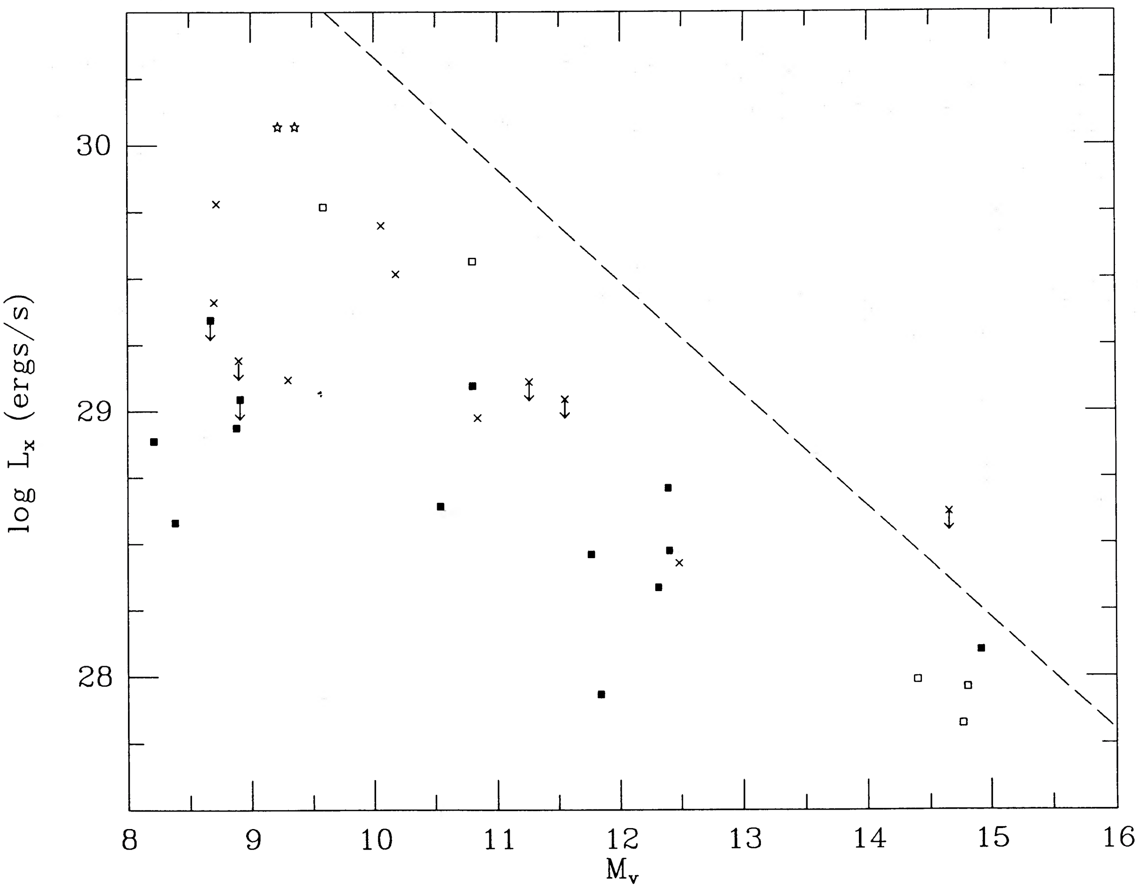


FIG. 3a

FIG. 3.—(a) Soft X-ray (0.3–3.5 keV) luminosity vs. absolute visual magnitude for the EMSS subsample of M dwarfs. Crossed symbols indicate $v \sin i > 10$ km s^{-1}; solid symbols indicate $v \sin i < 10$ km s^{-1}; 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). (b) Ratio of soft X-ray luminosity to bolometric luminosity vs. absolute visual magnitude. Symbols are identical to (a).

our own data in Figure 3. Figure 3a plots L_x versus M_V and Figure 3b plots $L_x/L_{\rm bol}$ versus M_V. Figure 3a shows a lack of detections in the upper right-hand corner, implying that the maximum L_x possible for an M dwarf decreases with spectral type. However, Figure 3b shows no such drop-off. In order to resolve the spread in $L_x/L_{\rm bol}$, we have plotted Figure 3 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.

We can attempt to quantify this relationship by plotting $L_x/L_{\rm bol}$ versus $v \sin i$ (Fig. 4). Unfortunately, our inability to measure $v \sin i$ below 10 km s^{-1} severely limits the number of points which can be fitted. Fitting the data above $v \sin i = 10$ km s^{-1}, we find

$$L_x/L_{\rm bol} \propto v \sin i^{0.9 \pm 0.8},$$

which is a fairly inconclusive result. By plotting $L_x/L_{\rm bol}$ rather than L_x, we reduce the scatter introduced by the dependence of L_x on $L_{\rm bol}$. Fitting L_x gives the same exponent for $v \sin i$ with greater error. We will present more conclusive results regarding the L_x versus $v \sin i$ relation in a forthcoming paper, where we consider all late-type stars from the EMSS subsample.

Finally, it is most desirable to relate L_x directly to the stellar mass (M). Using the empirical M versus $L_{\rm bol}$ relation of Smith (1983), we 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 Figure 5. Ideally, one would wish to include the rotation dependence in this function. However, for the reasons stated above, we are unable to do this.

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

Our data support 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 $E_{\rm rot} = I\omega^2/2$ and the moment of inertia, I, is proportional to M. Instead, L_x depends on mass in a similar manner as $L_{\rm bol}$, 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.

Now we must reconcile this result that L_x appears to decrease with decreasing mass, with the conclusion in § III that

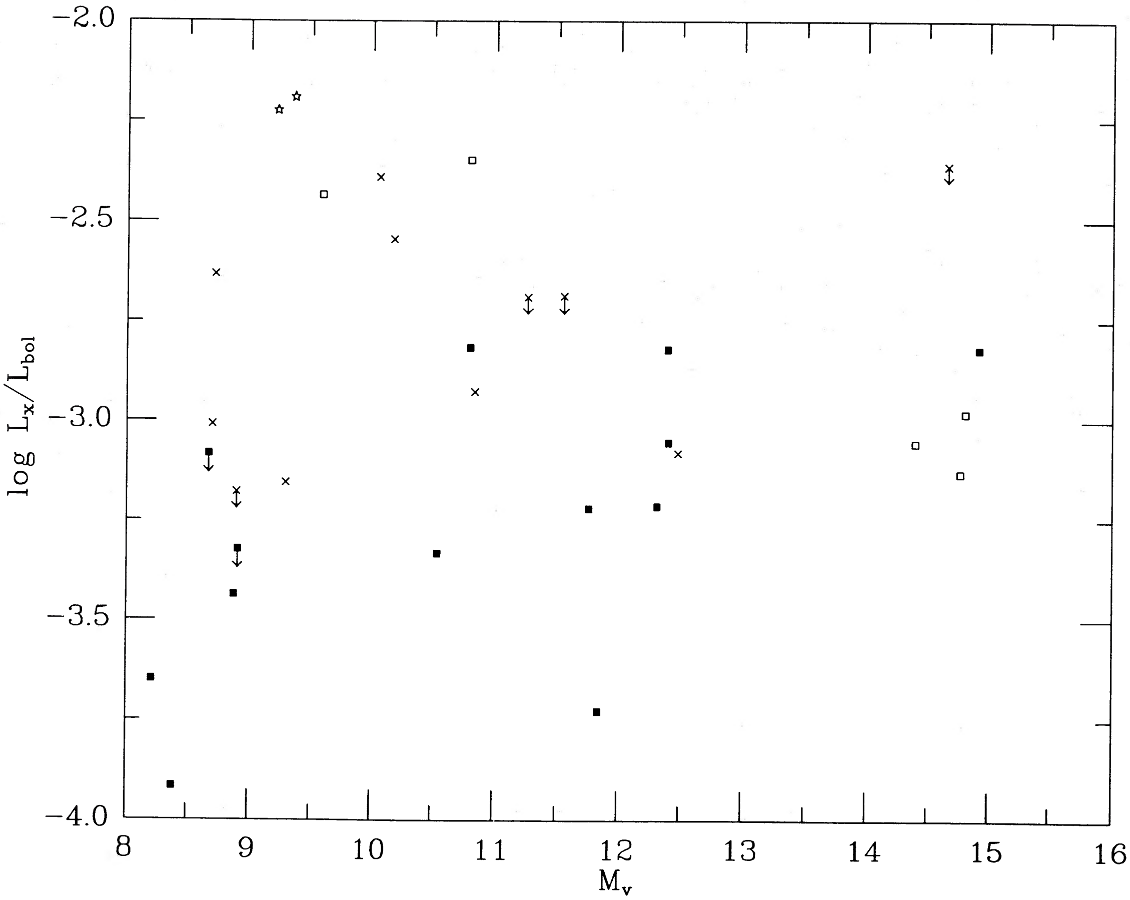


FIG. 3*b*

the overall fraction of M dwarfs which exhibit strong X-ray emission increases with decreasing mass.

This behavior can be explained if the spin-down time scales 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. These 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.

V. LIMITS ON LATE M DWARFS

As was mentioned above, no dwarfs later than M5 were detected in our 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. We consider the latter possibility first.

The luminosity function (LF) 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 LF are summarized by Reid (1987), who adopts an "averaged" LF from all sources, including samples of nearby stars, those derived from proper motion catalogs, and those obtained from red color surveys. The space density of late M dwarfs with $15.5 < M_V < 20$ from Reid's adopted LF is 23.5 M dwarfs per 10^3 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 LFs 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). Second, the Hawkins (1986) color survey (see also Reid 1987) indicates that the LF may turn sharply upward 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!

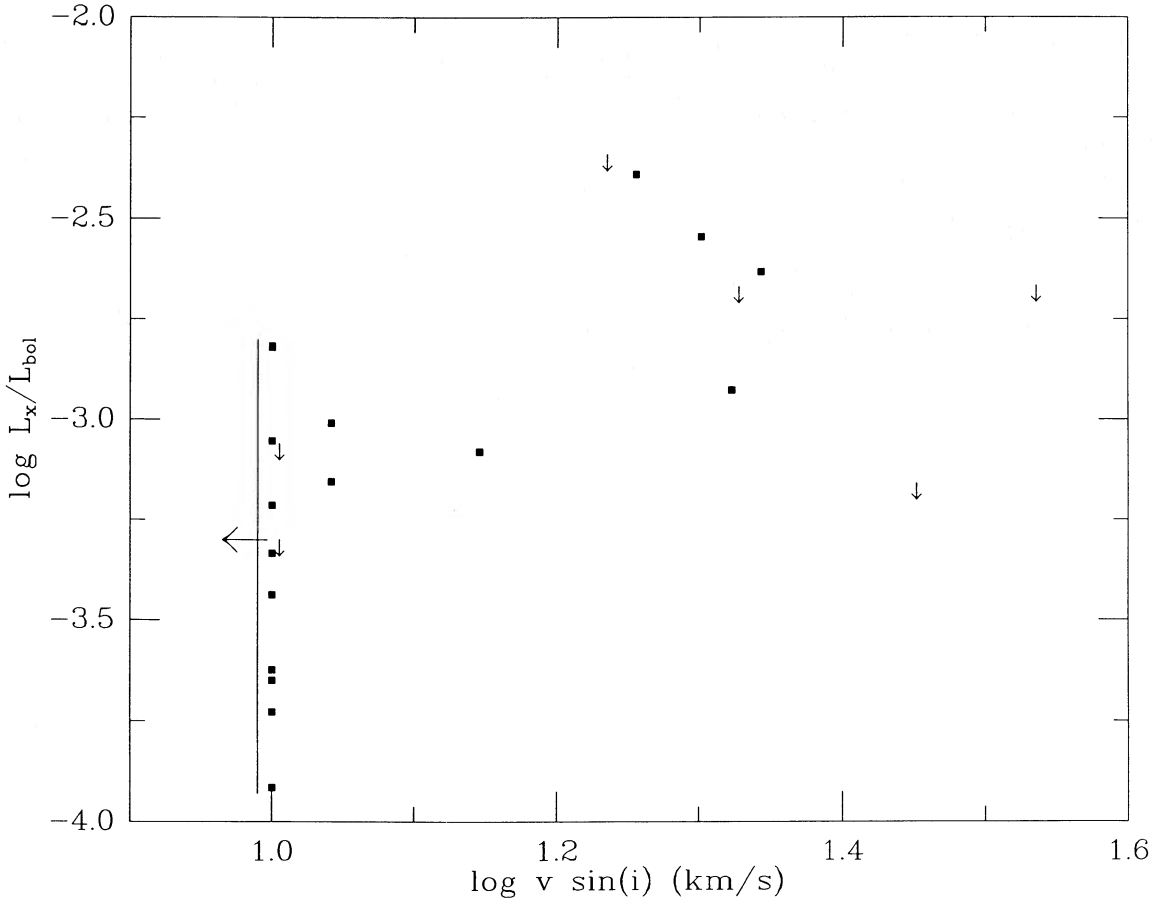


FIG. 4.—X-ray to bolometric luminosity ratio vs. projected rotational velocity for the EMSS M dwarf subsample. Arrows indicate upper limits on L_x. All points plotted at $v \sin i = 10$ km s^{-1} are actually < 10 km s^{-1}.

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.

Thus, we utilize the "averaged" space density of late M dwarfs—23.5 per 10^3 pc^3—calculated from Reid (1987), recognizing that it could be seriously in error, perhaps by as much as a factor of 2. 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, our 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, six 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 show 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 we extrapolate the L_x-mass relation down to 0.08 $M_\odot$, we 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 our 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, we sample a volume of space insufficient to contain even one of these stars. Therefore, we cannot answer the questions above since the X-ray fluxes involved are below our sensitivity limits.

VI. RELATIONSHIP BETWEEN CHROMOSPHERIC AND CORONAL ACTIVITY

The appearance of Ca II H and K and Hα 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 sample is classi-

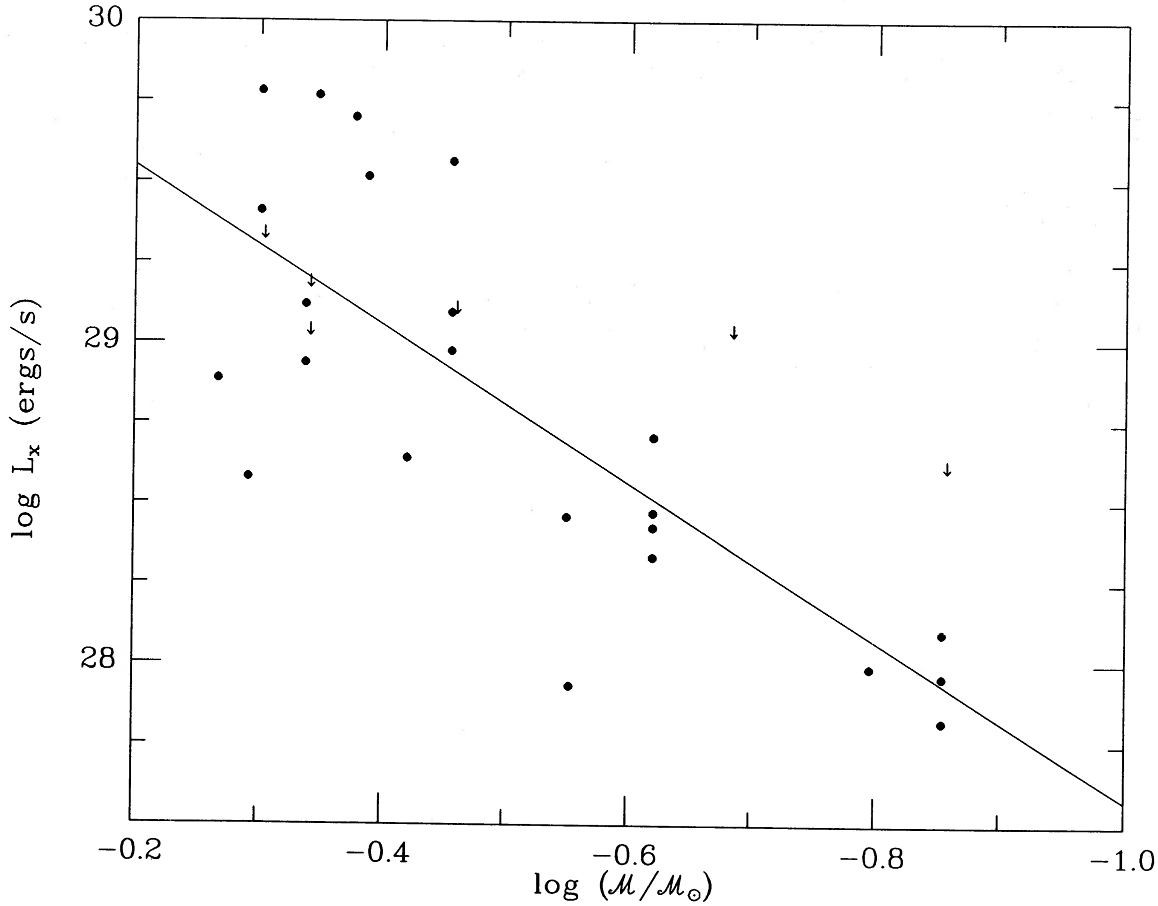


FIG. 5.—Soft X-ray (0.3–3.5 keV) luminosity vs. stellar mass for the EMSS M dwarf subsample. The solid line represents a least-squares fit (slope = −2.5) to the data, excluding upper limits and the PMS stars.

fied as Me. However, an Hα absorption profile can also be indicative of an active chromosphere, but one of smaller electron density (Cram and Giampapa 1987).

Of the two non-Me stars in the sample, one shows no Hα at low resolution and one has no Hα 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 Hα absorption profile, yet not enough to show Hα in emission. Giampapa, Cram, and Wild (1988) confirm this intermediate status for Gliese 900 through analysis of the Ca II H and 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 Hα in absorption or weakly in emission.

In order to investigate the empirical relationship, if any, between chromospheric and coronal activity, we compare L_x with the levels of chromospheric Hα 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 our sample, since it consists almost entirely of dwarfs. Furthermore, we 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 our procedure, any errors in the assigned distances cancel in the comparisons.

Figures 6*a*, *b*, and *c* are log-log scatter diagrams of L_x versus $L_{\mathrm{H}\alpha}$, L_x versus $L_{\mathrm{Ca\,II\,K}}$, and $L_{\mathrm{Ca\,II\,K}}$ versus $L_{\mathrm{H}\alpha}$ 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. But Figure 6 does show a definite correlation. M dwarfs with higher X-ray luminosities also radiate more at Ca II K and Hα. Skumanich *et al.* (1984) have already shown this for Hα. Their result was $\Delta L_{\mathrm{H}\alpha} = 0.2 L_x$. We have drawn this relation on Figure 6*a*. Our data deviate from this relation at the high-luminosity end, but this could be a result of catching some stars in flare. The sample's $\langle L_{\mathrm{H}\alpha}/L_x \rangle$ is 0.15.

We would like to get some qualitative idea of the slopes of the relations in Figure 6. However, in the manner which they are plotted, any errors in the distance measurements will tend

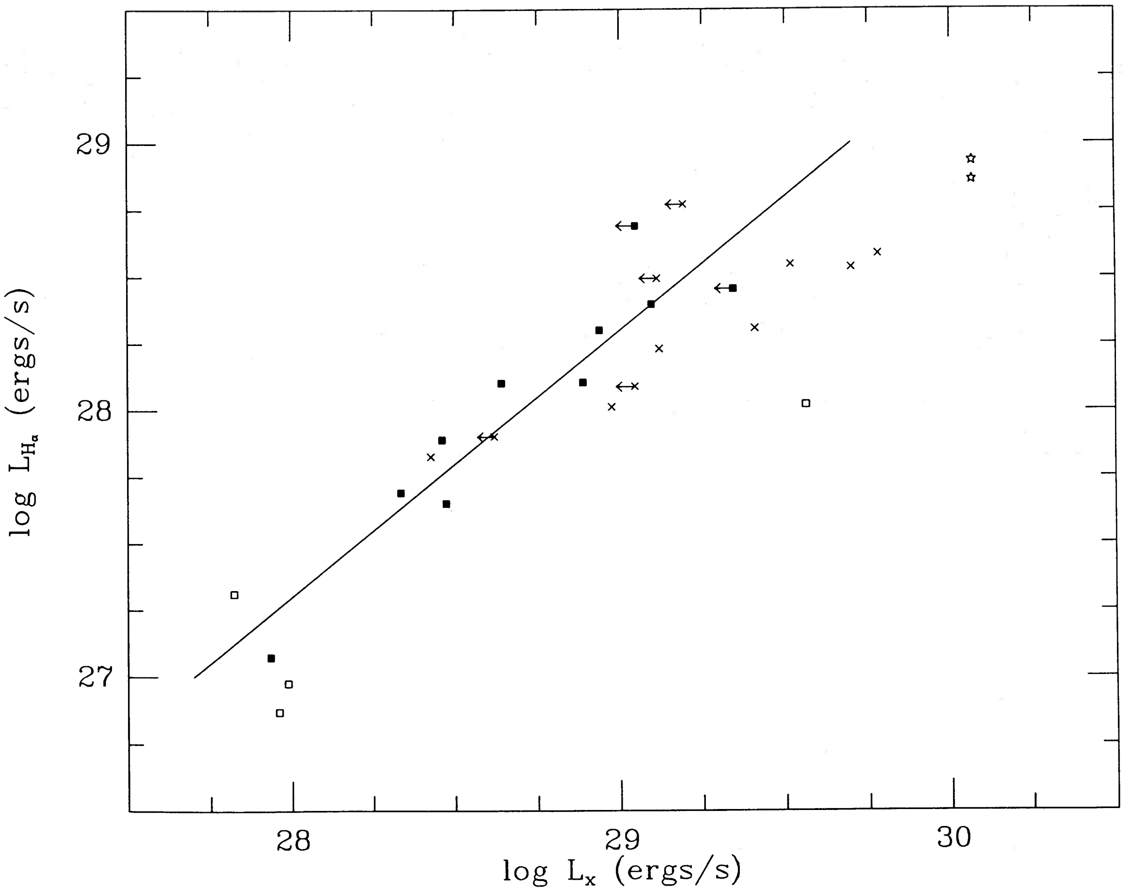


FIG. 6a

FIG. 6.—Comparison of coronal and chromospheric fluxes for the EMSS M dwarf subsample: (*a*) soft X-ray (0.3–3.5 keV) luminosity vs. Hα luminosity; (*b*) soft X-ray (0.3–3.5 keV) luminosity vs. Ca II K line luminosity; (*c*) Ca II K line luminosity vs. Hα luminosity. All symbols are identical to those in Fig. 3. The solid line in (*a*) represents the relation $\Delta L_{H\alpha} = 0.2 L_x$ found by Skumanich *et al.* (1984).

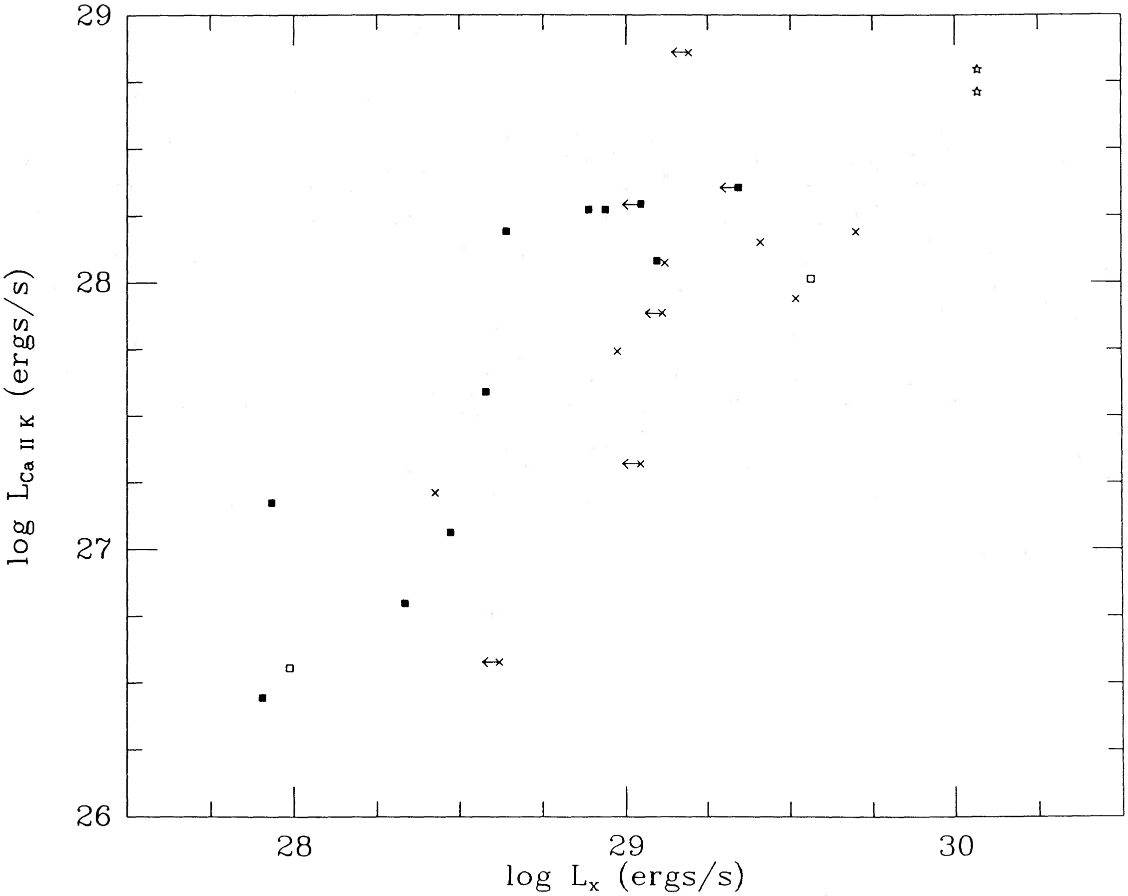
to bias the slope toward a value of 1. Therefore, we consider the same relations, but with each quantity ratioed to L_v to take out any distance (as well as radius) dependences. This is equivalent to plotting f_x/f_v, etc. Simple linear regressions give slopes of (*a*) 0.70 for $L_{H\alpha}$ versus L_x; (*b*) 0.50 for $L_{Ca\,II\,K}$ versus L_x; (*c*) 1.03 for $L_{H\alpha}$ versus $L_{Ca\,II\,K}$.

Looking at the information above, it seems reasonable that Hα 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 Hα 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), we 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 Hα, Ca II K, and unambiguous L_x measurements, we multiply $L_{H\alpha}$ by 1.78 to allow for flux from the entire Balmer series and multiply $L_{Ca\,II\,K}$ by 1.83 to include Ca II H. We then ratio the sum to L_x and find a $\langle L_{Balmer+Ca\,II}/L_x \rangle$ of 0.40. From data of Linsky *et al.* (1982), we calculate that $L_{Balmer+Ca\,II}/L_c \approx 0.77$ 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 our sample.

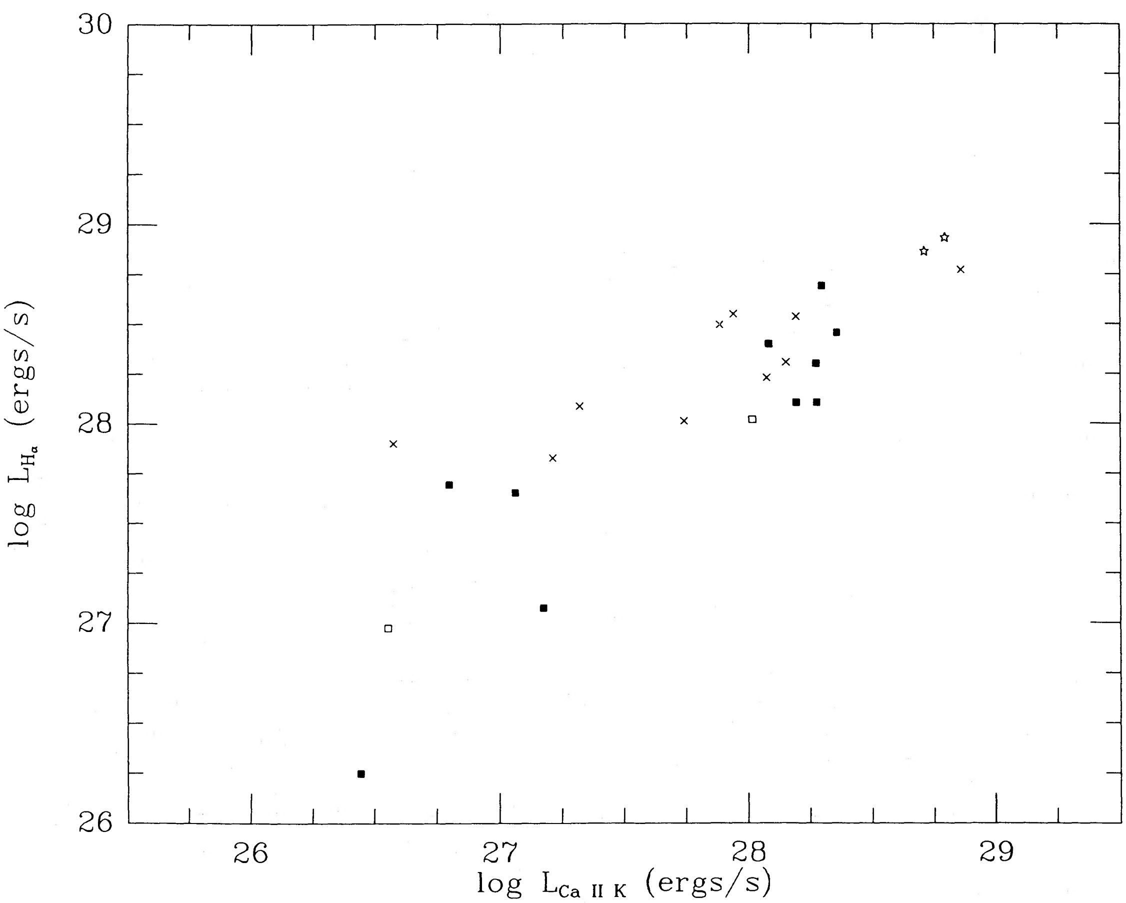
The result that $\langle L_c/L_x \rangle < 1$ is consistent with the model of coronal X-rays as the dominant source of chromospheric heating, assuming all the important contributors to chromospheric radiative cooling have been identified. Conversely, our result may be a manifestation of a common mechanism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

Figure 7 plots the Hα and Ca II K data in the same format as Figure 3. It shows that Hα luminosity does not drop off as quickly with L_{bol} as do L_x and $L_{Ca\,II\,K}$. But of more interest is the fact that the scatter due to rotation is smaller in Figure 7 than in Figure 3. This could be the result of a "saturated" chromosphere as described by Skumanich (1986, 1985). Beyond a rotational velocity of about 5 km s^{-1}, 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 and K as $R'_{HK} = 1.07 \times 10^{-4}$, where $R'_{HK} \equiv \Delta L_{HK}/L_{bol}$. Our data indicate that $\langle L_{Ca\,II\,K}/L_{bol} \rangle = 6.03 \times 10^5$. After multiplying by 1.83 to allow for the H line, we find a saturation value of 1.10×10^{-4}, in



29
28
27
26
28
29
30
log L$_{Ca\ II\ K}$ (ergs/s)
log L$_x$ (ergs/s)

FIG. 6b



30
29
28
27
26
26
27
28
29
log L$_{H_\alpha}$ (ergs/s)
log L$_{Ca\ II\ K}$ (ergs/s)

FIG. 6c

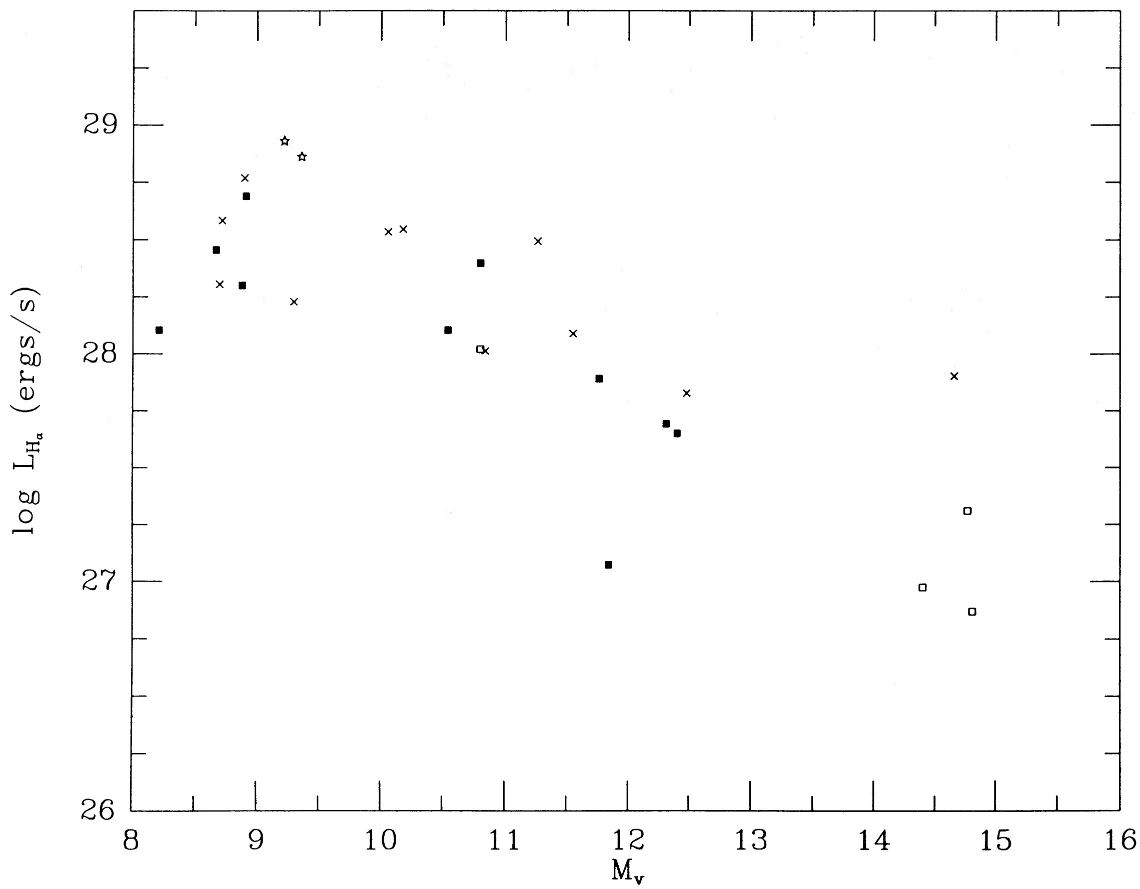


FIG. 7a

FIG. 7.—Absolute visual magnitude vs. (*a*) Hα luminosity and (*b*) Ca II K line luminosity. The symbols are identical to those in Fig. 3. Notice the decreased scatter due to rotation in Fig. 7 compared to Fig. 3.

agreement with Skumanich and MacGregor. If Ca II is indeed saturated, then our data indicate that this effect is stronger in the chromosphere than in the corona.

VII. SUMMARY

We have presented an X-ray selected, flux limited sample of M dwarfs. Analysis of this sample confirms previous results from analysis 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^{-1}; (2) the X-ray "bright" M dwarfs are the Me dwarfs, though, perhaps, mostly the single Me dwarfs; (3) L_x decreases with $L_{\rm bol}$, while $L_x/L_{\rm bol}$ remains constant through M5; (4) L_x is a function of rotation.

The limited kinematic information for the sample indicates that the nearby (<20 pc) members of the sample belong to the young disk, while rotational velocities indicate that $10^8 \leq \tau \leq 1 - 3 \times 10^9$ yr. 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 $L_x/L_{\rm bol}$ remains constant after M5, or whether it drops at the mass where M dwarfs become fully convective. We put an upper limit on X-ray luminosity for late M dwarfs of log $L_x = 27.45$. 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 cannot be strong X-ray emitters.

Finally, we find that L_x correlates with Hα 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 cannot be ruled out since the estimated total chromospheric luminosity for the whole sample is half the value of L_x.

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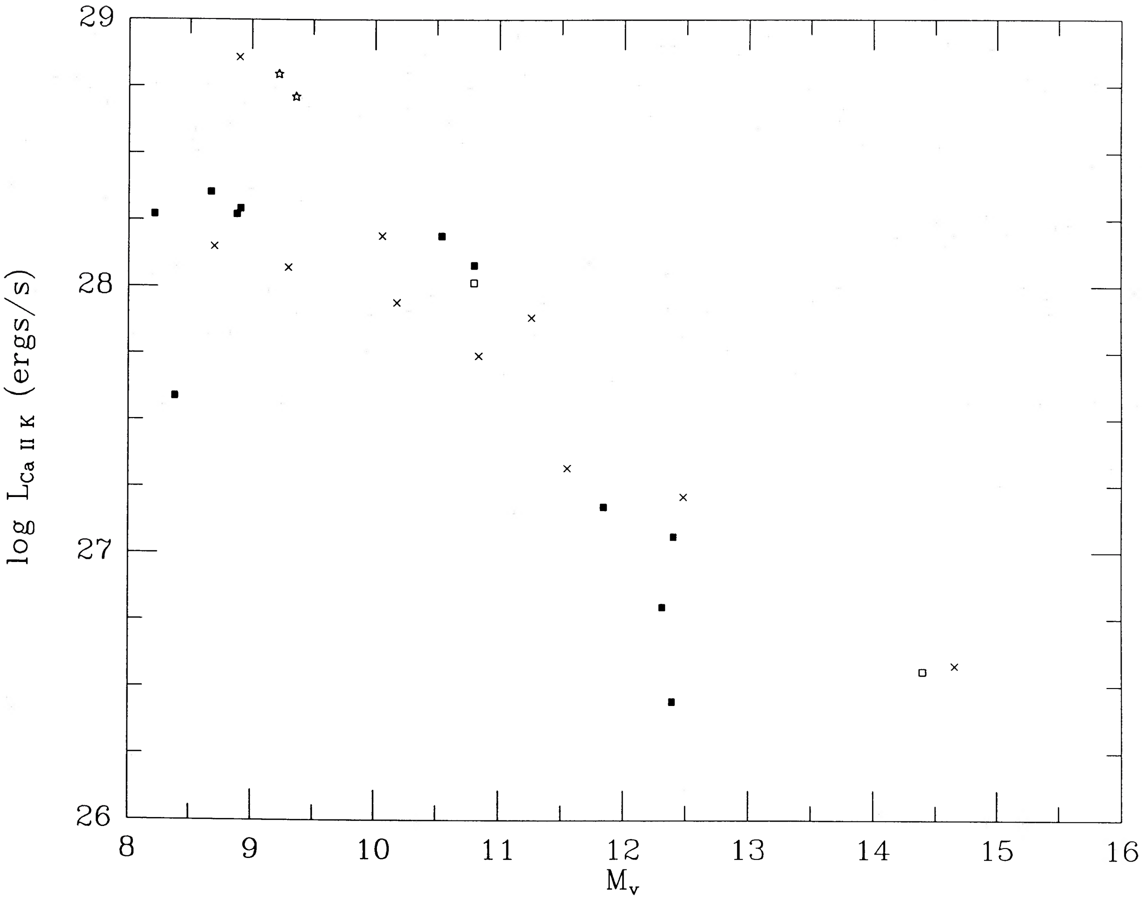

FIG. 7*b*

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