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A MAGNITUDE LIMITED STELLAR X-RAY SURVEY AND THE F STAR X-RAY LUMINOSITY FUNCTION

K. TOPKA,[1] Y. AVNI,[2] L. GOLUB, P. GORENSTEIN, F. R. HARNDEN, JR., R. ROSNER,[3] AND G. S. VAIANA
Harvard-Smithsonian Center for Astrophysics
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ABSTRACT

We have conducted an X-ray survey of stars brighter than visual magnitude 8.5 that have serendipitously fallen into the fields of view of the Imaging Proportional Counter of the *Einstein Observatory* (*HEAO 2*). The survey includes 227 separate $1° \times 1°$ fields, containing 274 stars with $V \leq 8.5$ and covering a wide range of spectral types and luminosity classes. X-ray emission was detected from 33 stars, and upper limits have been determined for the remainder of the sample. F type stars dominate the detected sample, and most of these are shown to be dwarfs. An X-ray luminosity function for dF stars has been deduced, and reveals that the average 0.2–4.0 keV luminosity of these stars is $\sim 10^{29}$ ergs s^{-1}. Constraints have been placed on the high luminosity tails and medians of the X-ray luminosity functions for other types of stars.

Subject headings: luminosity function — stars: coronae — stars: stellar statistics — X-rays: sources

I. INTRODUCTION

Theoretical calculations of stellar coronae, based upon standard models of shock heating via acoustic noise (see Ulmschneider and Bohn 1981, and references cited therein), have long suggested that at least some stars should possess coronae hot enough to be substantial X-ray emitters (see, e.g., Ulmschneider 1979). In particular, stars from late A to late G were expected to possess sufficiently vigorous convection zones, with associated substantial acoustic flux to produce solar-like hot coronae. These calculations, together with the detection of soft X-ray emission from several nearby stars (see review of Mewe 1979), led to the expectation that at least the closest stars in the spectral range A5–G8 would be detectable by the *Einstein Observatory*. Consequently, we have undertaken a magnitude limited survey (called the 8.5 Survey) of all stars brighter than visual magnitude 8.5 that fell within the fields of view of a large number of observations with the Imaging Proportional Counter (IPC) of the *Einstein X-Ray Observatory*. Stars in the A–G spectral range were frequently sampled by this survey, while O, early B, and dwarf M stars were not; O and early B stars are concentrated along the galactic equator (where the survey rarely sampled), and dM stars are nearly all fainter than $V = 8.5$. For these reasons only one O star and no dM stars were sampled, which explains why neither is well represented in the detected sample of the 8.5 Survey even though both O and dM stars are detected rather routinely in pointed observations (Harnden *et al.* 1979; Seward *et al.* 1979; Vaiana *et al.* 1981, hereafter Paper I; Rosner *et al.* 1981).

An earlier X-ray survey of a large number of stars was conducted by Vanderhill *et al.* (1975). No positive detections were obtained from a scan of about one-tenth of the sky at a limiting sensitivity of about 5×10^{-11} ergs cm^{-2} s^{-1} in the 0.1–0.28 keV band, implying that most types of stars could be rejected as significant contributers to the soft X-ray background (see, however, Rosner *et al.* 1981). Other surveys have also searched for X-ray emission from over 200 nearby stars (Margon, Mason, and Sanford 1974; Cruddace *et al.* 1975; Mewe *et al.* 1975, 1976; Garmire 1979; Topka *et al.* 1979); but aside from the RS CVn star surveys (Walter *et al.* 1980*a*, *b*), only a handful of detections were made.

The 8.5 Survey has considerably greater sensitivity than any of these earlier surveys, with a median sensitivity of 2.3×10^{-13} ergs cm^{-2} s^{-1} in the 0.2–4.0 keV band. It is part of a larger *Einstein Observatory* stellar X-ray survey (Vaiana *et al.* 1981), which includes, besides the 8.5 Survey, a pointed stellar survey, a serendipitous survey, and a "deep survey" (Giacconi *et al.* 1979*a*). In order to maximize the number of stars examined, we decided at the outset of the mission to supplement the limited number of stellar-pointed observations with a search for X-ray emission from optically bright stars falling serendipitously into nonstellar pointings. Some of the results of the 8.5 Survey are included in the preliminary results reported for the

[1] Now at Caltech, Pasadena, California.
[2] Also from Weizmann Institute, Rehovot, Israel.
[3] *Einstein Observatory* Guest Observer.

larger survey (Paper I), but the detailed luminosity function derived here for F stars, as well as constraints on the luminosity functions for A, G, and K stars, is new.

II. ANALYSIS

a) *Selection of Survey Fields*

The 8.5 Survey was conducted by selecting 227 IPC observations (from Center for Astrophysics data) and searching for stars brighter than $V=8.5$ that fortuitously fell within the images. The usable field of view of the IPC is $60' \times 60'$; but with 3$'$.2 wide rejection zones centered on each of the detector window support ribs, the geometric solid angle is reduced to ~ 0.8 square degrees. The IPC is described in detail by Giacconi *et al.* (1979*b*), and has an effective area of 100 cm^2 at 0.28 keV, and 130 cm^2 at 1.3 keV. The fields that comprise the 8.5 Survey contain 274 stars with $V<8.5$ and were selected (randomly by stellar content) according to criteria designed to maximize sensitivity by rejecting all fields with short exposures or with large extended or strong nonstellar X-ray sources (which have the effect of greatly increasing the effective background).

b) *8.5 Survey Procedure*

The stellar search was based upon SKYMAP, a star catalog containing positions and magnitudes for 255,461 stars (Gottlieb 1978) which is essentially complete down to $V=8.5$ and contains some fainter stars to tenth magnitude. After a list of survey stars was generated for a given field, a source detection program searched that X-ray image for an X-ray source near the position of each optical survey star. Whenever an X-ray source was detected, identification with an optically bright star was made on the basis that position coincidence between the X-ray source and the star be better than 70$''$. Within an error circle of this radius, and with a density of stars with $V<8.5$ determined from the survey (1.53 stars per square degree, Table 1), the probability of spurious position coincidence with a star brighter than $V=8.5$ is rather small ($\sim 10^{-3}$); for the 274 stars sampled, 0.4 spurious identifications are expected, indicating that virtually all of our 33 optical identifications are correct.

The observed count rates (both detections and upper limits) were converted into absolute fluxes using the conversion factor:

$$1 \text{ IPC count s}^{-1} = 2 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}. \quad (1)$$

This conversion factor was adopted because computer simulations, which folded a range of different thermal spectra (including emission lines derived for a solar abundance plasma) through the mirror and detector response functions, show that the conversion factor in the 0.2–4.0 keV band does not change by more than 20% between temperatures of 10^6 and 10^7 K. A study of the pulse height spectra of stars from the larger Center for Astrophysics survey shows that this is the expected temperature range for most stellar coronae (Paper I). This single conversion factor has been used for the reduction of all 8.5 Survey observations.

TABLE 1

PARAMETERS OF THE 8.5 MAGNITUDE LIMITED SURVEY

Parameter	Value
Observation epoch	1978 Dec 16 to 1979 Jul 07
Total IPC fields	227
Solid angle per field	0.79 square deg
Total solid angle	179 square deg
Exposure times:	
Minimum	420 s
Median	2300 s
Maximum	56000 s
Energy band	0.2–4.0 keV
Sensitivities:	
Minimum (ergs cm^{-2} s^{-1})	1.1 E−12
(L_x/L_v)	4.5 E−04
Median (ergs cm^{-2} s^{-1})	2.3 E−13
(L_x/L_v)	8.3 E−05
Maximum (ergs cm^{-2} s^{-1})	3.4 E−14
(L_x/L_v)	1.8 E−06
Total number of stars ($V<8.5$)	274 (1.53±0.09 stars per sq deg)
Detections (3 σ)	33 (12.0%)
Upper limits	241

Because the distances to most stars in the 8.5 Survey are not known, we usually cannot calculate the soft X-ray luminosity L_x [ergs s^{-1} in the 0.2–4.0 keV band] from the apparent flux f_x [ergs cm^{-2} s^{-1} in the 0.2–4.0 keV band]. The only parameter that can be calculated for *all* stars in all our surveys is L_x/L_v, the ratio of soft X-ray to visual-band luminosity (L_v is the luminosity in ergs s^{-1} in the band defined by the visual magnitude system). L_x/L_v can be calculated from the observed soft X-ray flux and the apparent visual-band flux f_v [ergs cm^{-2} s^{-1}] using the most recent absolute calibration of Vega:

$$L_x/L_v = f_x/f_v = 2.96 \times 10^5 f_x 10^{0.4V},$$

$$V = \text{visual magnitude}, \quad (2)$$

where equation (1) is used to calculate f_x. For nearby stars, interstellar optical extinction and X-ray absorption are negligible, and L_x/L_v is independent of distance.

III. RESULTS

Some parameters of the 8.5 Survey are given in Table 1. Thirty-three of the 274 survey stars were detected in soft X-rays, and their optical and X-ray properties are tabulated in Table 2. L_x/L_v (or an upper limit thereto)

TABLE 2

Stars Detected by the 8.5 Magnitude-Limited Survey

HD	R.A.	V	M_v	Seq	Counts	$\log f_x$	d(pc)[a]
SAO	Decl.	$B-V$	Sp	Survey	Eff Exp Time (s)	$\log L_x/L_v$	$\log L_x$
3914	$00^h39^m17^s.54$	7.08	...	573	64	−13.12	...
036585	40°24′52″.7	...	F5		16986	−4.82	...
5028	00 49 01.37	7.09	...	592	13	−12.09	55 S
255713	−71 25 23.6	...	F5 V		322	−3.79	29.5
28122	04 25 49.70	8.06	...	414	17	−12.86	...
013163	64 56 33.3	...	F0		2462	−4.16	...
28736	04 29 25.08	6.38	3.6	350	853	−12.40	36 S
111879	05 18 15.7	0.41	F4 V	351	43324	−4.38	28.8
28946	04 29 27.25	7.93	6.2	350	112	−13.33	23
111893	05 16 57.1	...	K1 V	351	47884	−4.69	27.34
37484	05 35 41.96	7.22	...	3720	218	−12.61	...
170610	−28 39 16.1	...	F5		17794	−4.25	...
37495	05 35 47.31	5.31	3.6	3720	605	−12.17	25
170613	−28 43 04.6	0.46	F4 V		17795	−4.57	28.71
37627	05 36 35.92	8.06	...	3720	127	−12.85	...
170631	−28 51 50.4	...	F0		18130	−4.16	...
75976	08 51 00.18	7.07	...	500	38	−12.20	260 S
098202	14 01 14.7	...	A3 III		1222	−3.91	30.7
76081	08 51 41.22	8.03	...	500	21	−12.26	...
098219	14 26 07.5	...	G5		758	−3.57	...
94765	10 53 54.92	7.34	...	915	17	−12.46	...
118578	07 39 20.8	...	K0		979	−4.05	...
95638	11 00 17.14	7.15	...	850	33	−12.33	45 S
015379	61 55 25.9	...	F7 V		1416	−4.00	29.0
103928	11 55 32.98	6.42	...	443	15	−12.68	56 S
062774	32 33 09.2	...	F0 V		1438	−4.64	28.9
105824	12 08 15.97	7.30	...	353	50	−13.06	...
044064	40 10 10.4	...	A3		11447	−4.67	...
105881	12 08 38.23	7.98	...	353	164	−12.69	...
062883	39 24 29.8	...	F5		16241	−4.03	...
108102	12 22 31.80	8.15	4.5	565	67	−11.96	71 S
082295	25 50 14.7	0.52	F7 V		1223	−3.23	29.8
108693	12 26 38.65	7.94	...	542	33	−12.95	...
063020	31 40 00.7	...	G0		5869	−4.30	...
110350	12 38 54.74	7.72	...	145	25	−12.01	...
100106	19 20 57.0	...	K0		508	−3.45	...
114723	13 09 41.09	7.20	...	549	27	−12.48	...
063396	32 21 01.2	...	F8		1644	−4.13	...
117721	13 30 00.66	8.05	...	476	321	−12.18	195 S
224234	−46 36 15.9	...	A3 V		9823	−3.49	30.5
126695	14 24 21.87	8.23	...	140	105	−11.99	...
101027	16 38 17.2	...	F8		2029	−3.22	...
138157	15 27 26.13	7.33	...	806	56	−12.05	...
101580	16 21 46.1	...	K0		1252	−3.65	...
151067	16 40 32.55	7.24	...	273	51	−12.43	...
017187	62 24 07.9	...	B8		2733	−4.06	...
152287	16 50 31.58	8.09	...	919	85	−12.11	...
208153	−30 19 34.1	...	A5		2212	−3.41	...
161247	17 42 27.39	8.16	...	951	35	−12.83	...
185707	−28 23 16.2	...	F5		4751	−4.10	...
177620	18 59 58.67	8.29	...	893	12	−12.49	...
009295	70 37 32.9	...	K0		743	−3.70	...
186160	19 40 26.17	7.98	...	354	57	−13.23	...
162928	−10 47 54.6	...	F8		19541	−4.57	...
192020	20 09 35.65	7.95	...	827	64	−12.95	89 S
069576	38 14 57.9	...	K1 IV		11358	−4.30	29.0
206267	21 37 24.26	5.62	−5.5	1012	35	−11.58	770
033626	57 15 44.4	0.21	O6.5 V		657	−4.53	32.27
206482	21 38 47.88	7.44	...	1012	14	−12.23	...
033652	57 21 14.5	...	F5		477	−3.78	...

TABLE 2—*Continued*

HD SAO	R.A. Decl.	V $B-V$	M_v Sp	Seq Survey	Counts Eff Exp Time (s)	$\log f_x$ $\operatorname{Log} L_x/L_v$	d(pc)[a] $\operatorname{Log} L_x$
208632 127190	21 54 59.41 03 55 08.7	7.00 ...	... F5	3959	41 11270	−13.14 −4.87	... ...
209779 145866	22 03 28.18 −05 36 05.6	7.55 ...	... G0	130	24 1010	−12.32 −3.83	... ...
221971 091372	23 33 56.84 20 23 20.3	7.75 ...	... F2	156	32 2214	−12.54 −3.97	... ...

[a]An S in the last column denotes that the distance was derived via spectroscopic parallax. Quoted luminosities for these stars are only approximations.

tected stars and detection thresholds for detected stars, is given in Table 3. K stars dominate the total sample, but F stars dominate the detected sample. The distributions of L_x/L_v for all detections and upper limits as a function of spectral type are given in Figure 1. In § III*c* below we obtain the luminosity function (in terms of L_x/L_v) for dF stars, and then use this function to derive general properties of the luminosity function in terms of L_x.

a) *Composition of an 8.5 Magnitude-limited Stellar Sample*

Because most of the 8.5 Survey stars lie in the 7.5–8.5 magnitude range, we often lack optical information beyond position, apparent visual magnitude, HD spectral type, and proper motions. In order to interpret the X-ray results fully, it is important to understand the composition of a magnitude limited sample of stars. In particular, we have calculated the expected frequency in both spectral type and luminosity class of stars in an 8.5 magnitude limited sample, assuming the galactic latitude distribution of the actual 8.5 Survey fields.

Let the number density of stars of a given spectral type in the plane of the galaxy ($z=0$), and within the absolute magnitude range ($M_v+\frac{1}{2}, M_v-\frac{1}{2}$), be given by $\phi(0, M_v)$ pc^{-3}. We assume a simple exponential law governing the variation of ϕ perpendicular to the galactic plane, of the form

$$\phi(z, M_v)=\phi(0, M_v) \exp(-z/\zeta), \tag{3}$$

where $\zeta(M_v)$ is the scale height of the stellar population. The number of stars of a given spectral type within the absolute magnitude range ($M_v+\frac{1}{2}, M_v-\frac{1}{2}$) observed in a solid angle Ω with apparent magnitude less than V is given by

$$N(<V, M_v)=\int_\Omega d\Omega \int_0^{R(V, M_v)} dR\, R^2 \phi(R \sin b, M_v), \tag{4}$$

where b is the galactic latitude observed and $R(V, M_v)$ is given by the expression

$$R(V, M_v)=10^{1+0.2(V-M_v)} \text{ pc}, \tag{5}$$

assuming negligible interstellar extinction.

We have used equation (4) to calculate $N(<V, M_v)$, the number of stars of each spectral type per square degree with absolute magnitude in the range ($M_v+\frac{1}{2}, M_v-\frac{1}{2}$) and brighter than apparent visual magnitude 8.5. The luminosity functions $\phi(0, M_v)$ and scale heights $\zeta(M_v)$ were taken from Allen (1973), and ϕ was assumed to be uniform within the 1 mag wide bins which we used. The results are shown in tabular form in Table 4, where "Calc % of Giants," for instance, indicates the percentage of all stars of a given spectral type that are expected to be of luminosity class I, II, or III (supergiants and giants). We have grouped supergiants with giants (I, II, and III), and subgiants with dwarfs (IV and V), because we have insufficient X-ray detection statistics to consider luminosity classes I, II, and IV separately.

We have checked the validity of the results of the calculations giving the expected frequency of each luminosity class as a function of spectral type by counting the number of stars of each luminosity class in a random, magnitude limited sample of 100 stars for each spectral type from Volume **1** of the *Michigan Spectral Catalogue* (Houk and Cowley 1975), and by studying the proper motions of a random, magnitude limited sample of 100 stars each of G, K, and M stars from the *AGK3 Catalogue* (1975). In both cases we used samples whose galactic latitude distributions were similar to that of the 8.5 Survey. These two observational tests agreed with the calculations except at spectral type G, as shown in Table 5.

From the expected frequency of luminosity classes as a function of spectral type for an 8.5 magnitude limited survey, we conclude that (1) the survey samples mostly dwarf stars for spectral type F and earlier (for example, about 75% to 80% of all F stars sampled are expected to be dwarfs); (2) a vast majority of all K and M stars in the survey are giants; (3) G stars in the sample contain a significant number of both dwarfs (30% to 50%) and giants (70% to 50%).

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TABLE 3

274 STARS SAMPLED BY THE 8.5 SURVEY

SEQ	SAO	V	Sp	Threshold or Upper Limit[a] $\log L_x/L_v$
		O Stars		
1012	033626	5.62	O6.5 V	−4.97
		B Stars		
135	064769	4.14	B5ne	< −5.59
273	017187	7.24	B8	−4.25
303	093821	6.23	B8	< −5.04
350	111876	6.64	B9	< −5.13
489	094500	8.12	B8	< −4.06
550	097378	7.50	B9	< −3.54
768	252464	7.65	B9	< −4.07
796	101555	7.86	B5	< −4.02
806	101600	6.10	B8 V	< −4.68
827	069638	8.40	B2	< −4.28
1012	033615	7.43	B9	< −4.00
1012	033617	8.00	B3	< −3.74
1170	238561	8.43	B8 II–III	< −3.62
1230	012354	8.40	B0	< −3.86
1230	013369	6.78	B9	< −4.37
1237	023065	8.10	B5	< −3.66
3492	124358	6.89	B9	< −4.49
		A Stars		
129	146044	3.84	A0 V	< −5.73
129	146068	7.75	A3	< −4.21
171	081819	7.18	A2	< −4.20
215	006990	7.63	A0	< −4.00
235	063561	8.27	A3	< −3.70
251	027430	5.23	A2	< −5.07
252	081116	7.92	A2	< −4.20
264	191144	6.18	A0	< −4.61
303	093832	7.96	A2	< −4.17
350	111896	5.68	A3	< −5.68
353	044064	7.30	A3	−4.76
414	013193	8.06	A0	< −3.92
420	085021	5.14	A1 V	< −4.77
476	224215	8.05	A0	< −4.48
476	224234	8.05	A3 V	−4.46
482	074831	8.16	A0	< −3.99
487	047554	7.85	A0	< −3.89
500	098202	7.07	A3 III	−4.21
501	014590	5.46	A m	< −5.11
519	146067	5.78	A0	< −4.72
606	255692	8.48	A9 V	< −3.79
612	255690	6.86	Alm	< −4.20
616	255773	7.82	A p	< −3.75
618	255748	7.14	A1–2 V	< −3.72
721	220257	6.89	A3 V	< −3.75
797	101575	8.16	A3	< −3.82
805	101601	7.95	A5	< −4.01
806	101597	7.65	A0	< −4.06
827	069623	8.47	A2	< −4.27
854	208065	7.10	A3	< −4.40
885	139381	7.86	A2	< −3.68
891	067565	7.68	A0	< −4.12
906	147935	7.62	A5	< −4.06
919	208153	8.09	A5	−3.97
919	208176	6.34	A5	< −4.67
		A Stars (*continued*)		
925	103279	8.37	A0	< −3.64
929	088572	8.06	A0	< −3.84
1230	012371	7.52	A0	< −4.08
1230	012377	7.32	A0	< −4.15
3492	124373	8.06	A0	< −3.95
3584	083596	6.49	A1 V	< −4.94
4251	129460	8.16	A2	< −4.02
4265	017792	8.03	A0	< −4.05
		F Stars		
140	101027	8.23	F8	−3.80
156	091372	7.75	F2	−4.09
156	091392	7.34	F2	< −4.30
201	091372	7.75	F2	< −4.03
247	014552	8.06	F0	< −3.94
264	191186	7.96	F5	< −3.80
325	120983	7.98	F8	< −4.00
337	HD218280	8.39	F8	< −4.07
350	111879	6.38	F4 V	−5.38
353	062883	7.98	F5	−4.57
354	162928	7.98	F8	−4.61
414	013163	8.06	F0	−4.16
420	085045	6.80	F5	< −4.26
429	HD91536	8.49	F8	< −3.75
430	178419	8.38	F8	< −3.73
443	062774	6.42	F0 V	−4.67
443	062790	8.47	F5	< −3.68
460	016549	8.08	F8	< −3.86
501	014626	8.47	F5	< −3.77
519	146083	7.26	F0	< −4.28
528	164434	8.49	F8	< −4.07
549	063396	7.20	F8	−4.24
552	BD+24343	8.10	F8	< −3.77
565	082295	8.15	F7 V	−3.73
573	036585	7.08	F5	−4.83
575	036605	8.40	F3 IV-V	< −4.16
590	248269	6.22	F7 IV-V	< −4.55
590	248271	7.58	F8	< −4.03
592	255713	7.09	F5 V	−3.82
602	HD 2466	8.09	F8 IV–V	< −3.93
608	255629	7.31	F5 V	< −4.16
608	255642	6.64	F3–5 IV	< −4.58
619	255689	7.44	F6 V	< −4.02
619	255698	7.79	F6 IV–V	< −3.83
626	255813	7.80	F0 IV–V	< −3.97
767	124039	7.69	F5	< −4.19
767	124085	7.65	F5	< −4.25
804	BD +142884	8.43	F0	< −3.51
804	BD +142891	8.32	F5	< −3.64
811	101651	7.05	F0	< −4.25
817	251362	7.70	F0–2 IV	< −4.14
817	251365	8.47	F3 V	< −3.91
850	015379	7.15	F7 V	−4.26
859	147415	6.60	F8	< −4.18
891	067679	7.96	F0	< −3.92
951	185707	8.16	F5	−4.16
1012	033652	7.44	F5	−3.78

TABLE 3—*Continued*

SEQ	SAO	V	Sp	Threshold or Upper Limit[a] $\log L_x/L_v$
		F Stars (*continued*)		
1237	023019	8.44	F0	< −3.72
3720	170610	7.22	F5	−4.81
3720	170613	5.31	F4 V	−5.64
3720	170631	8.06	F0	−4.51
3959	127190	7.00	F5	−5.00
4249	BD +3215	8.18	F0	< −4.03
4258	082121	8.47	F5	< −3.91
4309	119484	7.90	F8	< −4.34
		G Stars		
130	145866	7.55	G0	−3.98
140	101037	7.62	G5	< −3.92
161	084179	7.12	G8 V	< −4.48
199	091412	7.52	G0	< −4.46
215	006996	8.13	G5	< −3.99
237	083469	7.81	G0	< −3.99
252	081122	8.34	G5	< −4.09
255	015700	8.44	G5	< −3.85
278	100105	7.95	G0	< −4.29
313	017173	8.40	G5	< −3.87
322	065213	7.66	G0	< −4.19
334	146867	8.15	G0	< −3.98
350	111887	8.46	G0	< −4.52
423	027476	7.97	G5	< −3.81
439	193076	7.54	G5	< −4.11
439	193078	8.34	G5	< −3.96
445	063286	7.74	G5	< −4.24
445	063287	7.94	G0	< −4.10
466	007000	8.34	G5	< −3.98
490	096672	5.62	G6 III	< −4.74
494	008140	6.65	G0	< −4.72
500	098219	8.03	G5	−3.62
510	017342	7.82	G5	< −4.04
520	016204	8.03	G5	< −3.71
542	063020	7.94	G0	−4.32
551	154177	6.06	G7 III	< −4.32
552	126729	7.62	G5	< −3.96
590	248281	5.45	G7 III	< −4.79
612	HD 3395	7.86	G5 III	< −3.97
616	255779	7.46	G8 III	< −3.87
721	220256	7.75	G0	< −3.47
792	121010	7.99	G0	< −3.73
801	101603	7.18	G0	< −4.23
803	101612	7.93	G5	< −3.97
804	101594	7.92	G5	< −3.74
804	101595	8.20	G5	< −3.74
806	101602	8.03	G5	< −3.84
827	069597	7.21	G5	< −4.73
847	234461	7.41	G8 III–IV	< −4.19
891	067566	5.99	G5 II–III	< −4.78
1230	012346	7.38	G5	< −4.31
1239	022993	6.31	G8 III	< −4.62
3959	208776	6.94	G0 V	< −5.11
4293	191651	4.47	G9 III	< −5.49
4313	100157	8.50	G5	< −4.06
4317	100153	7.72	G5	< −4.17
4317	100165	8.43	G5	< −4.00

SEQ	SAO	V	Sp	Threshold or Upper Limit[a] $\log L_x/L_v$
		K Stars		
130	145838	7.63	K0	< −3.97
130	145882	7.88	K0	< −3.84
133	145624	7.98	K0	< −3.91
142	BD +52807	8.36	K5	< −3.78
145	100206	7.72	K0	−3.92
155	108706	8.18	K0	< −3.87
171	081839	8.10	K2	< −3.95
191	092389	8.10	K5	< −3.83
208	092096	7.98	K0	< −3.83
237	083457	8.37	K5	< −3.87
264	191169	7.98	K0	< −3.88
265	146310	7.55	K2	< −4.44
270	109807	7.97	K0	< −4.14
271	029024	7.88	K0	< −4.08
294	091543	8.39	K0	< −4.11
314	165941	7.88	K0	< −3.91
325	120977	7.53	K5	< −4.16
350	111893	7.93	K1 V	−4.81
353	062869	8.20	K2	< −4.49
416	027815	5.09	K2 III	< −5.12
423	027506	8.10	K5	< −3.72
443	062767	7.99	K0	< −3.98
443	062779	7.91	K0	< −4.00
452	111303	7.67	K2	< −4.14
456	013342	8.39	K2	< −3.92
457	117466	8.08	K0	< −4.00
466	006988	8.19	K0	< −4.07
467	027724	5.52	K3 III	< −4.99
467	027733	8.08	K0	< −3.87
487	047592	8.50	K0	< −3.59
489	094464	8.39	K2	< −4.01
490	096633	8.39	K0	< −3.80
494	008162	7.44	K2	< −4.27
501	014624	7.98	K0	< −3.84
510	017311	8.00	K2	< −3.93
510	017312	6.11	K1 III	< −4.70
510	017337	7.88	K0	< −3.96
510	017348	8.01	K0	< −3.96
510	017349	8.50	K0	< −3.64
550	097434	8.08	K0	< −3.55
551	154119	6.91	K2	< −4.07
552	126723	7.07	K0	< −4.39
552	126724	8.10	K0	< −3.86
573	054074	7.36	K2 Ve	< −4.71
575	BD +41126	7.86	K0	< −4.30
590	248260	8.29	K4 III	< −3.71
614	255638	7.74	K3 III	< −4.14
621	HD 10102	8.43	K0 III	< −3.36
784	174391	4.59	K5 III	< −5.34
797	BD +152863	8.46	K0	< −3.68
805	BD +152879	8.46	K0	< −3.74
806	101580	7.33	K0	−4.09
806	101610	6.61	K2	< −4.42
809	101640	5.26	K0 IV	< −5.05
810	101617	8.06	K5	< −3.71
810	101634	6.07	K0 III	< −4.61
817	251368	7.37	K0 III	< −4.24
827	069576	7.95	K1 IV	−4.38

TABLE 3—*Continued*

SEQ	SAO	V	Sp	Threshold or Upper Limit[a] $\log L_x/L_v$
		K Stars (*continued*)		
827	069578	8.00	K2	<-4.34
842	102921	8.08	K0	<-3.85
847	234488	6.51	K5–9 III	<-4.65
850	015354	8.30	K0	<-3.74
853	136884	7.98	K0	<-3.76
853	136892	7.98	K0	<-3.86
861	109471	5.75	K2 V	<-4.82
883	082740	7.32	K0	<-4.37
891	067688	6.85	K0	<-4.33
893	009275	8.06	K5	<-3.63
893	009295	8.29	K0	-3.75
906	147940	8.08	K0	<-3.88
915	118578	7.34	K0	-4.14
929	088555	8.17	K5	<-3.78
947	051216	8.06	K5	<-4.03
947	051245	7.83	K5	<-4.17
949	185731	7.86	K5	<-4.08
949	185733	8.06	K5	<-3.94
1012	033634	8.29	K0	<-3.44
1170	HD 95171	8.43	K2–3 III	<-3.60
1230	012355	8.05	K2	<-4.04
1230	012356	7.64	K0	<-4.05
1237	023085	7.11	K0	<-4.11
1237	023097	8.39	K0	<-3.63
3492	124356	7.58	K0	<-4.12
3492	124372	8.20	K2	<-3.90
3720	170614	7.34	K0	<-4.79
3959	127180	7.86	K5	<-4.66
4063	186894	7.00	K0	<-4.18
4063	186912	7.36	K0	<-3.97
4066	009241	5.28	K0 II–III	<-5.18
4249	BD +2227	7.78	K0	<-4.18
4256	062098	8.39	K0	<-4.14
4265	017779	7.69	K0	<-4.23
4268	214890	8.42	K0	<-4.04
4309	119465	7.53	K5	<-4.43
4309	119466	6.89	K0	<-4.76
4309	119479	6.80	K2	<-4.75
4313	100178	8.29	K0	<-4.13
4313	100182	8.49	K0	<-3.95
4315	100178	8.29	K0	<-4.03
4315	100179	7.67	K0	<-4.34
4317	100162	7.63	K0	<-4.25
		M Stars		
209	074382	8.20	M0	<-3.89
337	191638	7.65	M3	<-4.30
414	013165	7.60	M2	<-4.27
445	063278	8.15	M2	<-3.95
792	101556	6.97	M0	<-4.23
797	101545	5.14	M0 III	<-5.07
814	101641	6.75	M4	<-4.28
817	HD 98817	8.30	M2 Iab/b	<-4.04
919	208221	5.36	M7 IIIe	<-5.02
925	103252	7.93	M1	<-3.88

[a] 3 σ upper limits are listed for all nondetections. Detection thresholds (not detected values) are given for the 33 detections. See Table 2 for detected L_x/L_v values.

b) Sensitivity and Selection Effects of the 8.5 Survey

There is a wide range of exposure times, and a corresponding spread in sensitivity, among the 8.5 Survey observations because of the widely varying scientific objectives which targeted the individual fields. Furthermore, the sensitivity varies with position within a given field because of both local background variations and vignetting (which reduces the effective area off axis). We have determined the minimum, median, and maximum sensitivity of the 8.5 Survey in terms of L_x/L_v, and have then converted these to X-ray sensitivities for each spectral type using the absolute magnitudes as a function of spectral type given by Allen (1973), and the relation:

$$L_x = 4.05\times10^{34}(L_x/L_v)10^{-0.4M_v}\ \text{ergs s}^{-1}. \quad (6)$$

The minimum, median, and maximum sensitivity of the 8.5 Survey as a function of spectral type for both dwarfs and giants is shown in Figure 2. All stars in our sample that exist in the region of the (L_x, spectral type)-plane above the minimum sensitivity curve were detected, even though they may have fallen into the field of view of the least sensitive observation; below the maximum sensitivity curve no stars were detected, even those in the most sensitive 8.5 Survey field. We see that the sensitivity of the 8.5 Survey varies greatly amoung different spectral types, and that the survey has its maximum sensitivity in soft X-rays for both giants and dwarfs at spectral type G. Also shown in Figure 2 are the spectral ranges that the 8.5 Survey effectively sampled for dwarfs (B5 to G) and giants (G to M). The 8.5 Survey did not sample a significant number of: K and M dwarfs because they are intrinsically too faint in the optical; supergiants because their space density is too low; or O and early B stars because they have an inappropriate galactic latitude distribution. Only pointed observations of the nearest O through G stars can effectively probe below the maximum sensitivity curves of Figure 2. Dwarf K and M stars can be sampled at high sensitivity without pointed observations if several hundred IPC observations are available; their space densities are high enough so that many will fall into the fields of view of a large sample of observations accidentally (Topka 1980; Rosner *et al.* 1981).

c) F Stars

Because of the large number of positive detections, the F star observations can be analyzed in more detail than those of other spectral types. Thirty-three percent of all F stars in the 8.5 Survey were detected (cf. Table 4), a much higher percentage than for any other spectral type. In the most sensitive portion of the survey, nine out of 11 F stars were detected in fields for which the threshold of detection was lower than $\log L_x/L_v = -4.50$ (the two not detected are subgiants). In contrast,

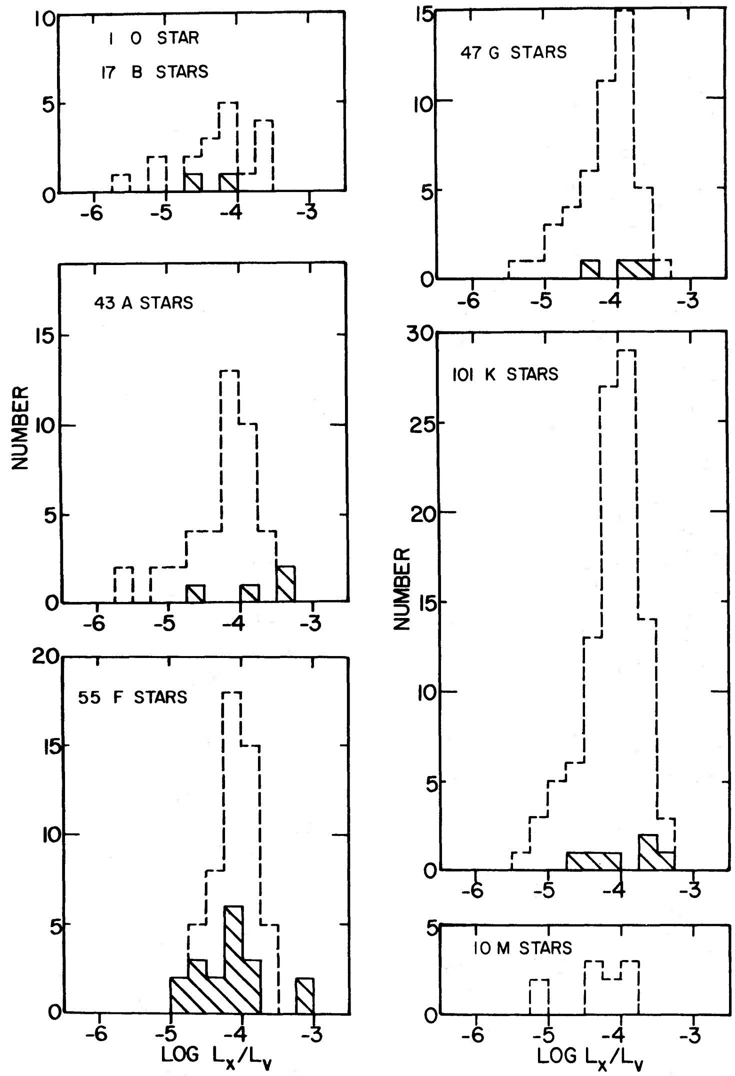

FIG. 1.—Histograms showing the distribution in L_x/L_v for all detections (*cross hatched*) and upper limits (*dashed lines*) for all 274 stars of the 8.5 survey, divided according to spectral type.

TABLE 4

STATISTICS OF DETECTIONS AND UPPER LIMITS OF THE 8.5 SURVEY

Total Survey						Most Sensitive Portion			
Sp	Stars Sampled	Calculated Number of Stars	Stars Detected	Calc % of Giants	Calc % of Dwarfs	Sp	Limit log L_x/L_v	Stars Sampled	Stars Detected
O	1	...	1	...	...	O	...	...	...
B	17	11	1	15	85	B	< -4.30	6	0
A	43	34	4	18	82	A	< -4.70	8	1
F	55	52	18	24	76	F	< -4.50	11	9
G	47	43	3	69	31	G	< -4.40	11	0
K	101	82	6	93	7	K	< -4.60	15	1
M	10	24	0	99.6	0.4	M	< -4.20	6	0
	274	246	33	(I, II, III)	(IV, V)			57	11

TABLE 5

Comparison of Calculated versus Observed Frequency of Giants and Dwarfs as a Function of Spectral Type[a]

	Dwarfs (IV–V)			Giants (I–III)		
Sp	Calc Freq. of IV–V	100 Stars AGK 3	100 Stars Michigan Catalog	Calc Freq. of I–III	100 Stars AGK 3	100 Stars Michigan Catalog
O	...	...	...	...	...	...
B	0.85	...	0.88	0.15	...	0.12
A	0.82	...	0.88	0.18	...	0.12
F	0.76	...	0.83	0.24	...	0.17
G	0.31	0.32	0.53	0.69	0.68	0.47
K	0.07	0.12	0.08	0.93	0.88	0.92
M ...	0.004	0.03	...	0.996	0.97	...

[a] For a complete 8.5 magnitude-limited stellar sample.

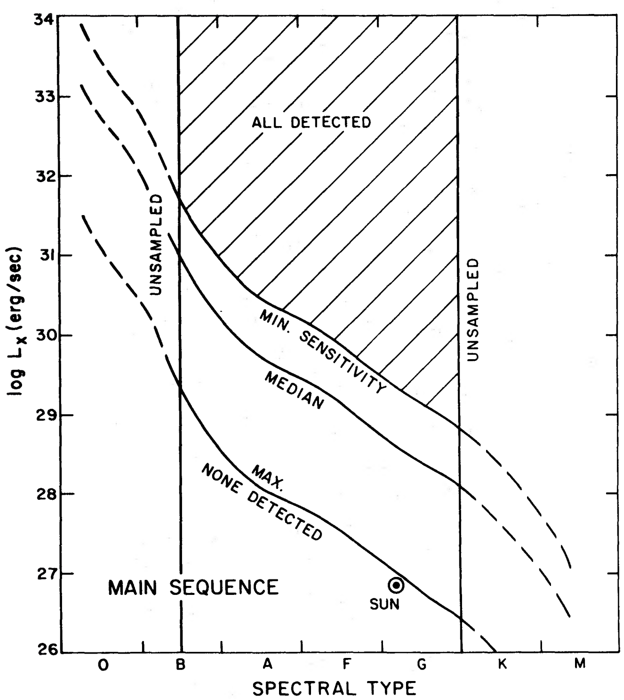

Fig. 2*a*

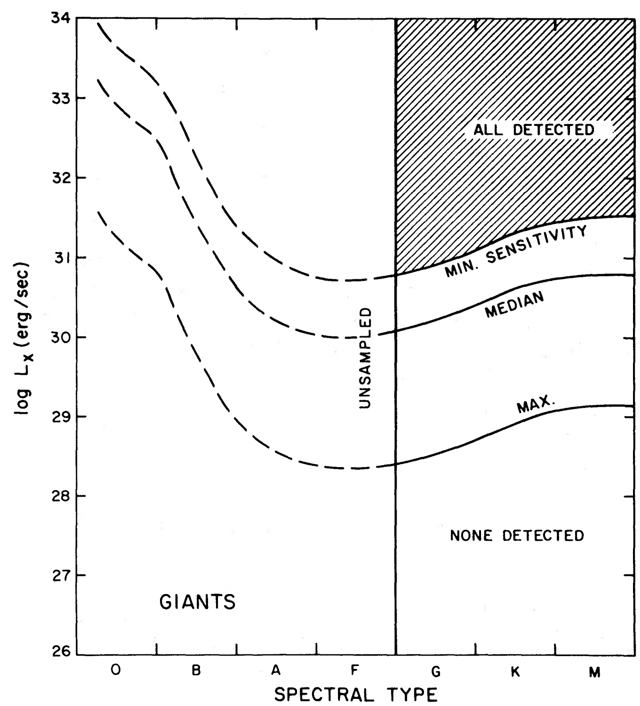

Fig. 2*b*

Fig. 2.—Sensitivity and selection effects for the specific stars of the 8.5 survey in the L_x versus spectral type plane for (*a*) dwarfs and (*b*) giants. The curve labelled "median" gives, as a function of spectral type, the value of L_x detectable in survey fields with the median sensitivity. Vertical lines show the limites in spectral type (B5–K0 for dwarfs, G–M for giants) between which a statistically significant sample of stars was obtained from our 8.5 magnitude limited survey. The region that the 8.5 survey most effectively sampled is shown crosshatched.

11 G stars were sampled at a sensitivity better than $\log L_x/L_v = -4.40$, but none was detected.

If a set of N observations of a certain population of stars have thresholds for detection that are all below the median, then more than $N/2$ (within statistics) must be detected, with $N/2$ detections (within statistics) above the median. From this criterion it is found that the 8.5 Survey at its most sensitive limit has definitely sampled below the median of the X-ray luminosity function for F stars. Nine F stars were observed with a sensitivity for detection better than $\log L_x/L_v = -4.57$, and eight of them were detected. Since five of the detected stars were measured to have L_x/L_v greater than this sensitivity level, the median probably lies near $\log L_x/L_v = -4.57$, as will be confirmed in detail below.

We believe that most, if not all, of the detected F stars are dwarfs (luminosity class V). This conclusion is based on the following:

i) Estimates based on stellar space densities (cf. Allen 1973) predict that about three-fourths of the F stars in the 8.5 Survey should be dwarfs (cf. Table 4). An 8.5 magnitude limited random sample of 100 F stars obtained from the *Michigan Spectral Catalogue* in fact contained 83 dwarfs and 17 giants.

ii) The characteristic L_x/L_v observed for the 18 detected 8.5 Survey F stars agrees with that measured for five F V and IV stars observed by the pointed survey of Paper I.

iii) There is some evidence from the pointed survey that giant and supergiant F stars have substantially lower median L_x/L_v than F dwarfs (Paper I). If the median value for F giants and supergiants is $\log L_x/L_v < -6$, as suggested by the pointed survey data, then most of these stars are unobservable in the 8.5 Survey because they are below the sensitivity limit ($\log L_x/L_v = -5.75$).

iv) Of those detected F stars which do have luminosity class information available in the literature, all (six) are dwarfs (V).

The arguments above and the evidence presented in Paper I together suggest that all of the detected F stars are dwarfs. Under this assumption about 43% of all F dwarfs in the sample have been detected.

The soft X-ray luminosity function [$\phi_x(L_x)$] for F stars cannot be directly determined because distances are unknown for most stars sampled by the 8.5 Survey. However, using the results of the 8.5 Survey we can obtain the luminosity function for dwarf F stars in terms of the variable L_x/L_v. We will assume that the X-ray to V-band luminosity ratio (L_x/L_v) is statistically independent of the V-band luminosity for dwarf F stars. If we let $\phi_x(L_x)$, $\phi_v(L_v)$, and $\phi_{xv}(L_x/L_v)$ be the normalized dF star luminosity functions for L_x, L_v, and L_x/L_v, then the means of these quantities are defined by

$$\langle L_x \rangle = \int_0^\infty dL_x L_x \phi_x(L_x), \tag{7}$$

with similar expressions for $\langle L_v \rangle$ and $\langle L_x/L_v \rangle$. Our assumption of statistical independence leads to:

$$\langle L_x/L_v \rangle = \langle L_x \rangle / \langle L_v \rangle. \tag{8}$$

Once we have obtained $\phi_{xv}(L_x/L_v)$ from the 8.5 Survey, we can derive properties of the function $\phi_x(L_x)$ because the optical luminosity function is known (cf. Allen 1973). The assumption of the statistical independence of L_x/L_v and L_v is important because of the nature of a magnitude limited survey, which always oversamples the more optically luminous members of any given stellar population because the more luminous stars are sampled in a larger volume of space than the less luminous. If (L_x/L_v) were correlated with L_v (for example, if optically luminous F stars were to have high L_x/L_v ratios), then a volume-limited (rather than magnitude-limited) sample of F stars would be required before the luminosity function could be obtained. Our assumption of the statistical independence of L_x/L_v and L_v is supported by data presented in Figure 3, which shows the variation of L_x/L_v versus spectral type (and thus versus absolute magnitude, since all or almost all are dwarfs) for 40 detected F stars from our larger stellar survey (Paper I). Of the 40 stars plotted in Figure 3, 18 come from the 8.5 Survey, while most of the rest come from the serendipitous survey. Adopting the absolute magnitude scale given by Allen (1973), and shown in Figure 3, we can calculate a visual-band luminosity using

$$\log L_v = 34.607 - 0.4\, M_v, \tag{9}$$

which yields a set of numbers ($\log L_v, \log L_x/L_v$) for each detected F star. We have tested for the presence of a linear correlation between $\log L_v$ and $\log L_x/L_v$ for these data; the correlation coefficient is -0.21. The probability that an uncorrelated sample of 40 data points would produce a larger correlation coefficient than ob-

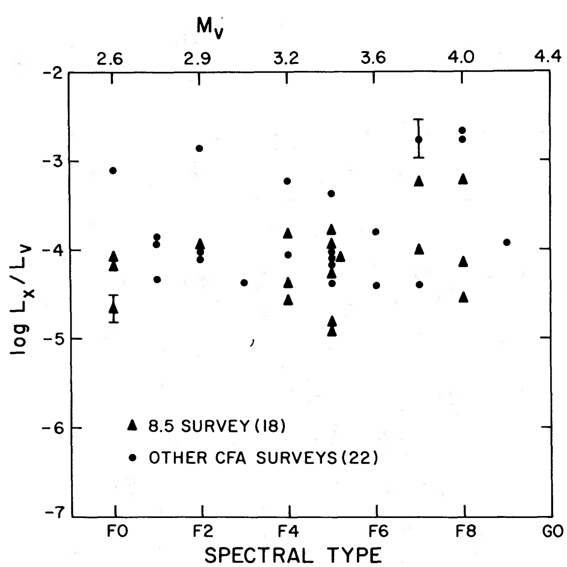

FIG. 3.—Plot of observed L_x/L_v versus spectral type for 40 detected F stars from the larger CfA stellar survey (Paper I). One detected F star, Canopus (F0 Ib), was omitted because it is known to be a supergiant. Most, if not all, of the other detections are main sequence stars. The data show that the median L_x/L_v does not change very much from F0 to F9, and therefore L_x/L_v is to first approximation independent of L_v.

served is 19%. Therefore, the correlation is not statistically significant, although a correlation in which $\log(L_x/L_v)$ rises by less than 1.0 from F0 to F9 cannot be excluded.

A detailed X-ray luminosity function has been constructed from the 8.5 Survey using the nonparametric, maximum likelihood analysis technique of Avni *et al.* (1980; see also Rosner *et al.* 1981 for similar analysis applied to dM stars). The results are shown in Figure 4, the unbinned integral luminosity function $[\Phi_{xv}(L_x/L_v)]$, and Figure 5*b*, the binned differential luminosity function $[\phi_{xv}(L_x/L_v)]$, where Φ_{xv} and ϕ_{xv} are related by

$$\Phi_{xv}(L_x/L_v)=\int_{L_x/L_v}^{\infty} dy\,\phi_{xv}(y), \quad \text{where } y\equiv(L_x/L_v). \tag{10}$$

The mean X-ray to V-band luminosity ratio can be obtained from either of these functions using:

$$\langle L_x/L_v\rangle=\int_0^{\infty} d(L_x/L_v)\Phi_{xv} = \int_0^{\infty} d(L_x/L_v)(L_x/L_v)\phi_{xv}. \tag{11}$$

For dF stars we obtain:

$$\log\langle L_x/L_v\rangle=-4.15^{+0.12}_{-0.10}. \tag{12}$$

The errors on the mean were also obtained from the maximum likelihood procedures described by Avni *et al.* (1980). In view of the earlier arguments that all F stars detected, and virtually all those sampled, are main sequence stars, the luminosity function derived here obtains for dF stars. We emphasize that what we have derived here is an observed luminosity function, not an intrinsic one; no allowance has been made for the effects of multiplicity (such as the contribution from optically fainter, but not necessarily X-ray fainter, companions).

We can also obtain the median L_x/L_v directly from the luminosity function presented in Figure 4. The result is $\log[\text{median}(L_x/L_v)]=-4.58$, which is in agreement with the estimate obtained earlier. The uncertainty in this median is the order of 0.15. An apparent difference between the median and the mean can also be seen in Figure 5*b*, which suggests that the dF luminosity function is not symmetric, but is skewed by the presence of a high-luminosity tail.

The mean V-band luminosity of dF stars can be calculated using the optical luminosity function given by Allen (1973); it is:

$$\log\langle L_v\rangle=33.20. \tag{13}$$

Using this result and the mean value of L_x/L_v obtained above, we can use equation (8) to obtain the mean X-ray luminosity for dF stars:

$$\log\langle L_x\rangle=29.05\pm0.11, \tag{14}$$

where the above luminosities are in units of ergs s^{-1}.

We could have chosen to express the optical and X-ray luminosity functions in terms of the variables $\log L_x$, $\log L_x/L_v$, and $\log L_v$, rather than L_x, L_x/L_v, and L_v. From the integral luminosity function of Figure 4, we can obtain a measure of the FWHM of $\phi_{xv}(\log L_x/L_v)$; it is FWHM $[\phi_{xv}(\log L_x/L_v)]=0.90$. The uncertainty in this quantity was estimated from the scatter in the measure of the point-to-point slope of the integral luminosity function of Figure 4, and is of order 0.20. Since L_x/L_v and L_v are assumed to be statistically independent variables, $\log L_x/L_v$ and $\log L_v$ are also independent, in which case the dispersions of $\phi_x(\log L_x)$, $\phi_{xv}(\log L_x/L_v)$, and $\phi_v(\log L_v)$ are related in

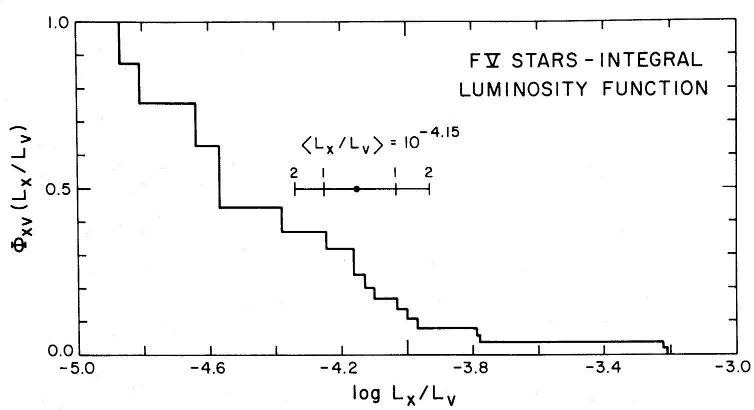

FIG. 4.—Normalized integral luminosity function Φ_{xv} for main sequence F stars, derived by maximum likelihood techniques (Avni *et al.* 1980) from *Einstein Observatory*/CfA 8.5 Survey observations. The mean X-ray to V-band luminosity ratio for these stars is $\log\langle L_x/L_v\rangle = -4.15(+0.12, -0.10)$, yielding a mean X-ray luminosity of $\log\langle L_x\rangle=29.05\pm0.11$.

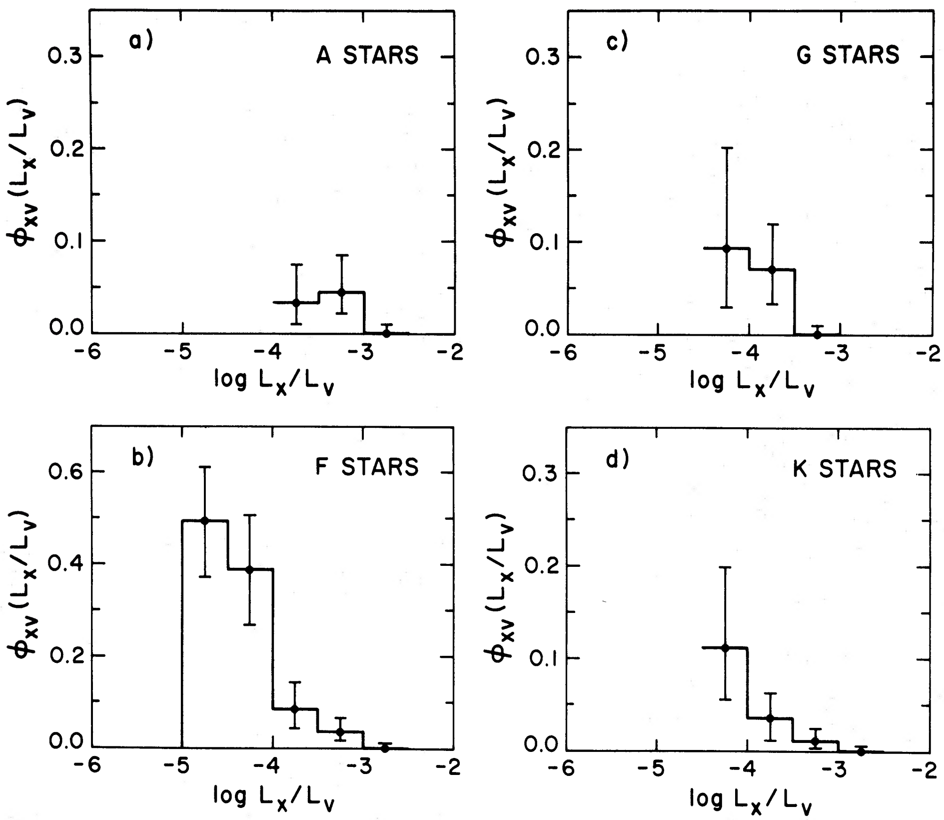

FIG. 5.—Differential luminosity functions for A, dF, G, and K stars, obtained using maximum likelihood techniques applied to 8.5 Survey observations. The luminosity function for dF stars is largely complete, while those for A, G, and K stars show only the high luminosity tails. Error bars are 68% confidence (1 σ). Note that stars in the spectral range A–K have similar maximum values of L_x/L_v. Note also that the vertical scale for dF stars is twice that for the others.

quadrature; and therefore approximately:

$$[\mathrm{FWHM}\ \phi_x(\log L_x)]^2 \approx [\mathrm{FWHM}\ \phi_{xv}(\log L_x/L_v)]^2 + [\mathrm{FWHM}\ \phi_v(\log L_v)]^2, \quad (15)$$

yielding for dF stars:

$$\mathrm{FWHM}\ \phi_x(\log L_x) \approx 1.2 \pm 0.2. \quad (16)$$

These results[4] are significant because they show that the width of the X-ray luminosity function ϕ_{xv}, as measured by the FWHM, is just as narrow as that of the optical luminosity function ϕ_v, and that the width of ϕ_x is only slightly larger than ϕ_v. The parameters of the X-ray luminosity function for main sequence F stars are given in Table 6.

[4]Since ϕ_{xv} and ϕ_v are known, we can explicitly calculate ϕ_x if we assume that L_x/L_v and L_x are independent variables. The results yield a mean of $\log \langle L_x \rangle = 28.92$, a median of 28.44, and a FWHM of 1.25, with estimated errors of 0.15, 0.15, and 0.2, respectively, in agreement with the values obtained above.

As a self-consistency test, an estimate of the mean L_x/L_v for dwarf F stars can also be obtained by comparing the optical and soft X-ray $\log N(>S)$–$\log S$ curves [$N(>S)$ is the number of stars per square degree observed above a given flux S (ergs cm^{-2} s^{-1})]. The values of $\log N(>S_x)$ obtained from the 8.5 Survey will be incomplete because of the survey optical cutoff at

TABLE 6

MAIN SEQUENCE F STARS: OPTICAL AND X-RAY LUMINOSITY FUNCTIONS

Parameter	Value (L_x, L_v in ergs s^{-1})
X-ray band (0.2–4.0 keV):	
Log median L_x/L_v	-4.58 ± 0.15
Log $\langle L_x/L_v \rangle$	$-4.15^{+0.12}_{-0.10}$
FWHM $\phi_{xv}(\log L_x/L_v)$ ...	0.9 ± 0.2
Log median L_x	28.44 ± 0.15
Log $\langle L_x \rangle$	29.05 ± 0.11
FWHM $\phi_x(\log L_x)$	1.2 ± 0.2
Visual band (Allen 1973):	
Log $\langle L_v \rangle$	33.20
$\langle M_v \rangle$	3.40
FWHM $\phi_v(\log L_v)$	0.84

TABLE 7

LOG $N(>S)$ VERSUS LOG S FOR F STARS

Log S (ergs cm^{-2} s^{-1})	Number of Stars Observed	Observed Log $N(>S)$	Corrected[a] Log $N(>S)$
X-ray (0.2–4.0 keV) band:			
>-12.30	4	$-1.65^{+0.29}_{-0.31}$	$-1.57^{+0.30}_{-0.32}$
>-12.75	12	$-1.04^{+0.11}_{-0.16}$	$-0.81^{+0.14}_{-0.18}$
>-13.20	17	$-0.63^{+0.10}_{-0.14}$	$-0.22^{+0.13}_{-0.17}$
Optical (visual) band[b]:			
>-7.87	...	-2.01	...
>-8.87	...	-0.51	...

[a]Corrected for optical cutoff at $V=8.5$.

[b]Assuming $n(0)=2.67$ E-03 F Stars per cubic parsec, and the optical luminosity given by Allen 1973.

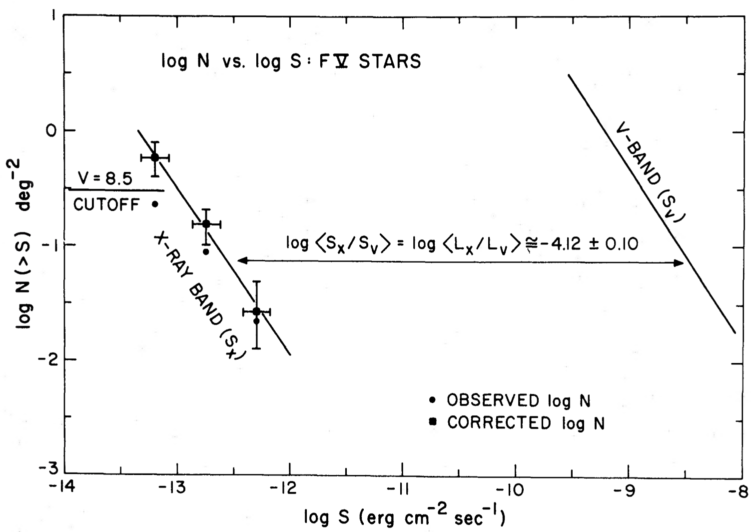

FIG. 6.—Log N–Log S curve for main sequence F stars in the visual band compared to data points in the soft X-ray band obtained from the 8.5 survey. A straight line of slope $-3/2$ has been fitted to the X-ray data. The fitted X-ray log N–log S line is 4.12 ± 0.10 orders of magnitude lower in flux than its optical counterpart. This provides an approximate measure of the mean value of L_x/L_v for dwarf F stars which agrees well with the value obtained from maximum likelihood calculations. Dots are observed X-ray log N values, while squares are the X-ray log N values corrected for the incompleteness due to the optical cutoff at $V=8.5$. Calculation of the corrections were based on the X-ray luminosity function given in Fig. 4 and the optical luminosity function given by Allen (1973).

$V=8.5$. However, because we already know the shape of both the X-ray and optical luminosity functions for dF stars, we can estimate the extent to which we underestimate $N(>S_x)$. The results of determining the optical and X-ray log $N(>S)$ for F stars are summarized in Table 7, and the calculated optical log N–log S_v curve and the X-ray log N–log S_x data points are shown in Figure 6. The optical log N–log S_v curve was calculated from the space density (adjusted slightly for the galactic latitude distribution of the 8.5 Survey) and optical luminosity function for F dwarfs provided by Allen (1973), and has a slope of $-3/2$. If we assume that the X-ray emitting properties of main sequence F stars are independent of distance from the Sun (homogeneity), then the slope of the X-ray log N–log S_x curve must be identical to that of its optical counterpart, regardless of the shape of X-ray luminosity function. If we fit a straight line (with slope fixed at $-3/2$) to the corrected log $N(>S_x)$ data points, we obtain a line shifted by -4.12 ± 0.10 orders of magnitude from the optical log N–log S curve (Fig. 6). This represents an approximation[5] to the mean value of L_x/L_v for main sequence F stars, and is consistent with $\langle L_x/L_v\rangle$ obtained above.

[5]Rigorously, this shift measures the log of the 2/3 power of the 3/2 moment of the L_x/L_v luminosity function. In many cases, including our F star luminosity functions, this measure differs only slightly from the mean.

We note from Figure 6 that the uncorrected value of the highest $\log N(>S_x)$ data point is close to the absolute cutoff imposed by the $V=8.5$ limit, which suggests that all dF stars are X-ray emitters and that at the survey limit we detected virtually all dF stars sampled.

d) *Other Stars*

A study of the most sensitive 8.5 Survey observations (see Table 4) shows that, except for F stars, the 8.5 Survey has been unsuccessful in detecting the stars sampled with the greatest sensitivity. If the most sensitive portion of a survey had thresholds for detection below the median luminosity, then at least one-half (within statistics) of the objects sampled would be detected. As this is definitely not the case for all spectral types sampled except F (Table 4), we cannot establish median X-ray emission levels for any other stars. The fact that several B, A, G, and K stars were detected (14 in all) shows that these stars, like F stars, have soft X-ray luminosity functions that possess high luminosity tails. Even though we cannot determine $\langle L_x/L_v \rangle$ for any other spectral types, we can extract valuable information about the high luminosity tails of A, G, and K star luminosity functions. The maximum likelihood calculations of Avni *et al.* (1980) are also valid for samples that do not reach the median, and can be used to calculate the shape of the high luminosity tails. This information is generally not obtainable from pointed surveys, for although they have greater sensitivity, the available pointed sample size limits the number of targets to a value too small to probe statistically infrequent features of luminosity functions, such as high luminosity tails (unless, as is the case with dM stars, the high luminosity tail is substantially populated, see Rosner *et al.* 1981).

Using the procedures mentioned above, we have calculated the high luminosity tails of the X-ray luminosity functions for A, G, and K stars. The results are presented in Figure 5. Detailed arguments were presented earlier to show that almost all F stars detected by the 8.5 Survey (as well as most of the F stars for which upper limits were obtained) are dwarfs. At present we do not possess such detailed information for the detected A, G, and K stars, so the high luminosity tails for these stars are undifferentiated with respect to luminosity class.

The partial luminosity functions shown in Figure 5 reveal that all spectral types from A to K have similar maximum values of L_x/L_v, despite gross differences in their median L_x/L_v values. For example, pointed observations of early A main sequence stars (Topka 1980) suggest that the median is near $\log L_x/L_v \approx -7$, while for F stars it is -4.5. Yet their high luminosity tails are similar. It is an interesting problem for future research to discover the properties of the A stars that are such intense emitters relative to the A star mean. Finally, our calculations allow us to place good statistical constraints on the fraction of stars in the spectral range A to K that have $\log L_x/L_v$ above -3.5 (best estimate is 2%; 3 sigma upper limit is 6%).

Although no other X-ray medians can be obtained, we can obtain upper bounds to the X-ray medians for stars from B to M. If no detections are obtained for the most sensitive portion of a survey, the fourth most sensitive upper limit is a $\sim 94\%$ confidence upper bound on the median luminosity. The probability of sampling

TABLE 8

CONSTRAINTS ON X-RAY LUMINOSITY FUNCTIONS FOR DWARFS AND GIANTS

Sp Range	Log Median Log L_x/L_v	Log Median L_x[a]	Lowest Upper Limit or Detection: Log L_x/L_v	Lowest Upper Limit or Detection: Log L_v[b]	Highest Detection: Log L_x/L_v	Highest Detection: Log L_x[b]
Main sequence:						
O6.5 V	...	...	...	...	-5.53	32.27
B5–B9 V........	<-4.70	<29.76	<-5.59	<28.8	-4.06	30.5
A0–A5 V	<-4.95	<28.91	<-5.73	<28.1	-3.41	30.4
F0–F9 V........	-4.58 ± 0.15	28.44 ± 0.15	-4.87	28.4	-3.22	29.8
mean	-4.15 ± 0.11	29.05 ± 0.11				
G0–G7 V	<-4.2	<28.30	<-5.11	<27.7	-3.62	28.9
G8–K2 V	<-4.48	<27.58	<-5.05	<27.2	-3.45	28.8
Giants:						
A0–A9 III	...	...	<-5.07	<28.7	-3.91	30.6
G0–G9 III......	<-4.72	<29.47	<-5.49	<28.7	...	...
K0–K9 III......	<-4.99	<29.52	<-5.34	<28.7	...	...
M0–M8 III	<-4.30	<30.41	<-5.07	<29.2	...	...

[a] Calculated using the optical luminosity functions of Allen 1973.
[b] Approximate values based on absolute magnitudes from Allen 1973.

below the median four times and obtaining only upper limits is at most 6% [$(0.5)^4$], and will often be much less than this. The principal complication involved with applying this technique is the fact that each spectral type observed by the 8.5 Survey is a mixture of luminosity classes. Fortunately, almost all of the best upper limits were obtained for the closest stars in the survey, and these are always the (optically) brightest stars. In consequence, there are more optical data available in the literature for the best upper limits than for the average 8.5 Survey star. In addition, our composition analysis for the 8.5 Survey predicts that almost all the best upper limits for B and A stars are for dwarfs; and for K and M stars, giants. We have therefore been able to distinguish the best upper limits for dwarfs from the best upper limits for giants.

Upper bounds to the median L_x/L_v and L_x have been determined for main sequence stars in the spectral range B5 to K2 and for giant stars from G to M. Several important trends are evident from the data displayed in Table 8. First, both G and early K dwarfs have a median L_x substantially lower than dF stars. If the Sun ($L_x \sim 10^{27}$ ergs s^{-1}) is near the median L_x for dG stars, then there is a very sharp drop of over two orders of magnitude in median L_x from late F to early G. Second, the median L_x either remains the same or actually drops from F to A. Third, there is probably a substantial rise in L_x from A to O. (One O6.5 V star was observed and easily detected; comparison of this observation with many other O stars observed by the serendipitous and pointed surveys [Harnden *et al.* 1979; Seward *et al.* 1979; Paper I] shows that this star exhibits normal O star X-ray emission.) For a larger list giving preliminary median X-ray emission levels as a function of spectral type, see Paper I.

IV. SUMMARY

The 8.5 Survey is composed of observations of 274 stars brighter than $V = 8.5$. Calculation of the expected composition of this survey shows that dwarfs dominate spectral types B, A, and F, while giants dominate K and M; the G star sample contains roughly equal numbers of both dwarfs and giants. The present 8.5 Survey has sampled a significant number of dwarfs in the range B5–K2; and giants have been substantially sampled from G to M. Most of 8.5 Survey fields are at high galactic latitude, effectively eliminating the possibility of sampling significant numbers of O and early B stars. X-ray emission was detected from 33 stars, 18 of which are F stars.

Near the limit of sensitivity of the 8.5 Survey ($f_x = 3.4 \times 10^{-14}$ ergs cm^{-2} s^{-1}), all dF stars brighter than $V = 8.5$ have been detected, suggesting that all main sequence F stars are X-ray emitters. The average X-ray emission level for main sequence F stars is 10^{29} ergs s^{-1} in the 0.2–4.0 keV band, about two orders of magnitude greater than the quiet Sun.

We have determined the dF star integral and differential X-ray luminosity functions; the results are presented in Figures 4 and 5, and in Table 6. The available evidence shows that the mean value of L_x/L_v for dF stars, as well as the dispersion in L_x/L_v around the mean, does not change substantially from F0 to F9. If $\langle L_x/L_v \rangle$ is constant from F0 to F9, the mean value of the X-ray emission, $\langle L_x \rangle$, must drop from approximately $10^{29.3}$ ergs s^{-1} at F0 V to about $10^{28.7}$ ergs s^{-1} at F9 V. The luminosity function ϕ_{xv} is skewed by the presence of a high luminosity tail, which is also evident for stars in the spectral range B5 to K2. The high luminosity tails of the luminosity functions for A, G, and K stars have also been determined. Two percent of all stars in the spectral range A0–K9 observed by the 8.5 Survey have L_x/L_v greater than $10^{-3.5}$, showing that the X-ray brightest stars in this spectral range have about the same value of L_x/L_v, a phenomenon not yet understood.

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Y. Avni, L. Golub, P. Gorenstein, F. R. Harnden, Jr., R. Rosner, and G. S. Vaiana: Center of Astrophysics, 60 Garden Street, Cambridge, MA 02138

K. Topka: Solar Astronomy 264-33, California Institute of Technology, Pasadena, CA 91125