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RESULTS FROM AN EXTENSIVE *EINSTEIN* STELLAR SURVEY

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ABSTRACT

We report the preliminary results of the *Einstein* Observatory stellar X-ray survey. To date, 143 soft X-ray sources have been identified with stellar counterparts, leaving no doubt that stars in general constitute a pervasive class of low-luminosity galactic X-ray sources. We have detected stars along the entire main sequence, of all luminosity classes, pre–main sequence stars as well as very evolved stars. Early type OB stars have X-ray luminosities in the range $\sim 10^{31}$ to $\sim 10^{34}$ ergs s^{-1}; late type stars show a somewhat lower range of X-ray emission levels, from $\sim 10^{26}$ to $\sim 10^{31}$ ergs s^{-1}. Late type main-sequence stars show little dependence of X-ray emission levels upon stellar effective temperature; similarly, the observations suggest weak, if any, dependence of X-ray luminosity upon effective gravity. Instead, the data show a broad range of emission levels ($\sim$three orders of magnitude) throughout the main sequence later than F0. Comparison of the data with published theories of acoustically heated coronae shows that these models are inadequate to explain our results. The data are consistent with magnetically dominated coronae, as in the solar case.

Subject headings: stars: coronae — X-rays: sources

I. INTRODUCTION

We report the preliminary results of an extensive, ongoing *Einstein* Observatory stellar survey. The observations discussed here involve the results of several distinct Harvard-Smithsonian Center for Astrophysics (CfA) observing programs (126 stars detected) as well as results provided by a number of collaborating Guest Observers (17 stars detected) and cover approximately the first 6 months of Observatory operation. These results are preliminary in nature; but because they provide a first overview of the levels of stellar X-ray emission throughout the H-R diagram, we felt that their intrinsic interest merited early dissemination.

The ongoing program has detected X-ray emission from stars and stellar systems throughout most of the H-R diagram (Fig. 1), and has established stars in general to be a class of low-luminosity ($< 10^{35}$ ergs s^{-1}) X-ray sources. The Observatory's high-efficiency imaging focal plane detectors and large collecting area optics combine to give a $\sim 10^3$ higher sensitivity for detection of point sources such as stars (Giacconi *et al.* 1979*b*) than previous surveys (cf. Vanderhill *et al.* 1975) and has therefore allowed detection of typical stellar X-ray emission levels. It can, therefore, now be asserted that X-ray

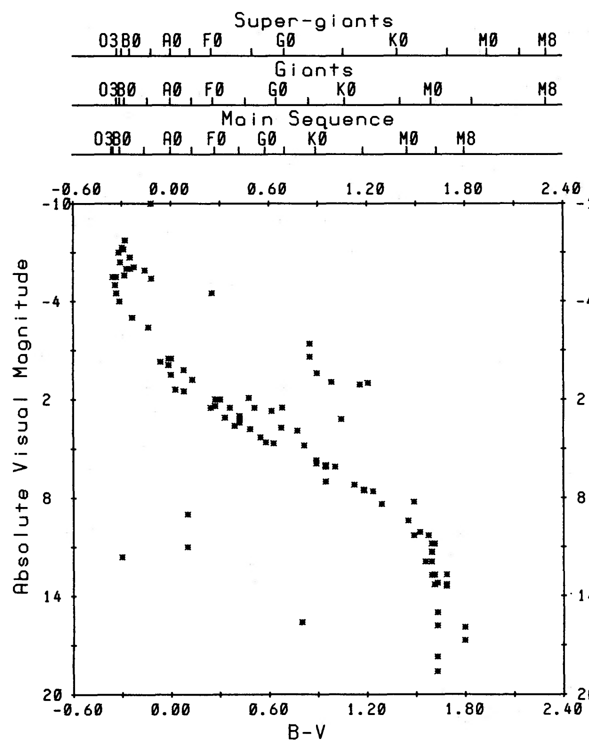

FIG. 1.—An H-R diagram for stars detected as soft X-ray sources by *Einstein*. The figure only includes that subset of Survey stars for which absolute visual magnitude could be determined either from the luminosity class or from parallax data; these stars are referred to as the "optically well-classified" sample.

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emitting stars are the norm, not the exception; and it is now possible, for the first time, to test coronal theories throughout the H-R diagram. If, as we shall contend, stellar X-ray emission generally derives from hot stellar coronae, the *Einstein* Observatory results reported here provide the first *direct* observation of coronal activity throughout the H-R diagram; they thus extend previous, more limited X-ray observations (Catura, Acton, and Johnson 1975; Heise *et al.* 1975; Mewe *et al.* 1975; Vanderhill *et al.* 1975; Nugent and Garmire 1978; Cash *et al.* 1978; Topka *et al.* 1979; Walter *et al.* 1980*a*, *b*) and complement other observations in the radio, infrared, optical, and UV regions (Oster 1975; Zirin 1975; Wilson 1966, 1978; Stencel 1978; Dupree 1975; Evans, Jordan, and Wilson 1975; Vitz *et al.* 1976; Brown, Jordan, and Wilson 1979; Carpenter and Wing 1979; Haisch and Linsky 1976; Linsky and Haisch 1979; Hartmann *et al.* 1979; Cassinelli and Olson 1979).

Our paper is organized as follows: we briefly define the objectives and components of our stellar survey program and outline the data analysis (§ II); the detailed results are described in § III, and their implications for stellar coronal theory are discussed in § IV. The major results are summarized in § V.

II. THE *Einstein*/CfA STELLAR SURVEY

a) *Objectives*

The basic observational goal[8] of the CfA stellar survey is to establish the X-ray luminosity function and spectral characteristics for classes of stars throughout the H-R diagram. Corollary studies include the identification of relevant stellar characteristics (viz., age, multiplicity, rotation, effective temperature) which correlate with the presence of X-ray emission and its intensity; investigation of stellar variability on various time scales, ranging from flare transients to rotational and orbital periods; and determination of the stellar contribution to diffuse galactic soft X-ray emission from stellar clusters and galaxies.

These studies are readily within the capability of the *Einstein* Observatory, as $\sim 10^4$ stars are estimated to be accessible at flux levels comparable to that of stars already detected. Constraints upon the available observing time will limit observations to $\sim 10\%$ of that number by mission end, but this should suffice for our present survey purposes for most types of stars. However, at the present preliminary stage of the survey, in which roughly one-half of the observed stars are serendipitous discoveries with little corresponding optical data available, our aims are more modest. Our present analysis strategy is, first, to estimate *typical* emission levels via the Pointed Survey (which samples the nearest stars); second, to define the *upper range* of emission levels via the remaining serendipitous and magnitude-limited surveys (which are biased toward the most luminous sources). Definition of the *lower range* of emission levels is as yet relatively incomplete and must await completion of the ongoing Pointed Survey.

b) *Organization*

The data reported here were acquired as part of four independent observing programs which collectively comprise the *Einstein*/CfA stellar survey: (1) the *Pointed Survey*, consisting of pointed observations of a sample of nearby stars in each spectral type and luminosity class category; (2) the *8.5 Survey*, presently entailing a search of all imaging proportional counter (IPC) fields for sources associated with stars brighter than $V = 8.5$ (Topka 1980); (3) the *Deep Stellar Survey*, conducted as part of the *Einstein* Deep Surveys (Giacconi *et al.* 1979*b*), consisting of a search of Deep Survey fields for sources identified with stars; and (4) the *Serendipitous Survey*, consisting of a search of all CfA IPC and high-resolution imager (HRI) fields (other than Deep Survey fields) for serendipitous sources which can be identified with stars regardless of stellar optical magnitude. Each of these programs, biased by selection criteria used and presently in various stages of completion, contributes unique information regarding the X-ray luminosity function of the various types of stars.

c) *Data Analysis*

The details of the Observatory instrumentation and methods of data reduction have been described by Giacconi *et al.* (1979*a*). Many details of the general analysis techniques can also be found in Giacconi *et al.* (1979*b*), Harnden *et al.* (1979*a*), and Seward *et al.* (1979).

Rigorous spectral analysis is not yet possible for sources observed with the IPC, although it does provide pulse height spectra spanning the 0.2–4.0 keV passband. However, qualitative comparisons have been carried out for a subset of the stronger IPC sources which includes a substantial number of early-type stars and selected late-type stars. These comparisons of their pulse height spectra with pulse height spectra of the remaining IPC sources have yielded the qualitative result that all stellar sources show spectra consistent with temperatures of the order of or lower than $\sim 10^7$ K. In consequence, we have used conversion factors of 2×10^{-11} ergs per IPC count and 4×10^{-11} ergs per HRI count to derive the provisional 0.2–4.0 keV X-ray fluxes.[9]

[8] These objectives have evolved somewhat as the initial data have been interpreted. The original "pointed" observing program was designed to be conservative and exploratory in keeping with the firm knowledge available at that time; however, "surprises" which would open up new areas of investigation were allowed for by establishing several extensive search programs for serendipitous sources. Several of the original guest observer programs have also been particularly valuable in this latter regard by providing exploratory pointed observations which could not *a priori* have been justified within the time constraints on consortium programs. These observations have been distinguished from the CfA results in our tabular presentations.

[9] These conversions were derived by folding solar abundance thermal spectra through the IPC instrument response, with the conclusion that the IPC conversion factor varies by less than 20% over the source temperature range 0.25 to 1.0 keV if interstellar absorption is negligible (i.e., log $N_H \leq 19$). Comparison of HRI and IPC observations of the same stellar sources shows that the HRI conversion factor can vary substantially in this temperature range primarily for early type (OB) stars, for which this effect has been taken explicitly into account.

d) *Tabulated Results*

The number of *Einstein* X-ray sources identified with stars as part of the present program stands at 143. A list of these survey sources, together with their optical counterparts, is presented in Table 1. These data represent results of observations obtained from 1978 December to 1979 August,[10] excluding only fields with strong diffuse sources in the field of view or with very short exposure times. The X-ray source names indicate the X-ray source positions; positioning accuracy depends somewhat on source strength, typically ranging from $\sim 40''$ for IPC sources to $\sim 4''$ for HRI sources. Fluxes are determined after background subtraction.

Because the basic motivation of the Survey is to study the dependence of stellar X-ray emission upon stellar properties, Table 1 has been segregated by spectral type and luminosity class. In addition to the stellar effective temperature and surface gravity, other possibly relevant parameters include the stellar rotation rate, mean surface magnetic field strength, strength of various emission lines (viz., Ca II H and K), and multiplicity; where readily available, these data have been considered in the following discussion. We are presently conducting a long-range program of optical studies of all stars associated with *Einstein*/CfA stellar survey sources in collaboration with optical observers and more detailed analysis (including spectral fitting) of the X-ray data.

e) *Luminosity and Flux Ratios*

The most outstanding result of the survey is that all categories of stars—with the sole exception of very late type giants and supergiants—have been detected as soft X-ray emitters; this is illustrated by the H-R diagram shown in Figure 1, which shows all stars observed as X-ray sources, and whose spectral type and luminosity class are known (this sample of stars will henceforth be called the "optically well-classified" sample).

An important parameter for comparing X-ray emission levels from different types of stars is the ratio of X-ray to bolometric luminosity $L_x/L_{\rm bol}$. In general this ratio can be computed only if both the spectral type and luminosity class of the star in question are available. Unfortunately, this is not the case for the majority of sources we have detected so far; many stars are relatively faint, and only color information is available. The available data will, however, allow us to compute—for *all Einstein* stellar sources—the X-ray flux to *V*-band flux ratio f_x/f_V. The ultimately desired ratio $L_x/L_{\rm bol}$ can then be derived if one knows (*a*) the extent of interstellar optical and X-ray extinction and (*b*) the proper bolometric correction.

Nevertheless, the f_x/f_V ratio does permit an immediate, qualitative insight into the variation of X-ray emission throughout the H-R diagram. Figures 2*a*–2*c*, which are plots of f_x/f_V versus spectral type show that X-ray emission is persistent along the entire main sequence, quite in contrast to expectations based upon traditional theories of coronal heating (see, for example, Mewe 1979). Since, as we shall argue below, we are in most cases seeing *typical* X-ray emission levels (and not *just* the exceptionally luminous stars), our data call for a major reassessment of theories of stellar coronal formation.

III. DETAILED SURVEY RESULTS

A detailed analysis of the survey data leading to the construction of X-ray luminosity functions involves a comparison of data from each of the four distinct observing programs for each spectral type and luminosity class. The following discussion outlines the principal results of our preliminary analysis, separating the available sample of stars by spectral type and luminosity class; this separation is motivated by past theoretical expectations of levels of stellar X-ray emission and by organizational convenience, and should not be interpreted as a substantive categorization. The artificiality of this separation is particularly evident for very early type stars, where no evidence exists for luminosity class differences, and for very late-type dwarfs (dK and later), where levels of X-ray emission do not appear to be related to spectral type.

a) *Early Type* (*O*, *B*, *and A*) *Main-Sequence Stars*

The data for early main-sequence stars include a dozen stars of spectral types ranging from O3 to A3, with a significant gap in the early B range due to the fact that the Pointed Survey has not as yet (e.g., as of the cutoff date for this report) sampled any stars in this spectral range. From a theoretical point of view, these stars are unified by the fact that they are conventionally not expected to have a vigorous surface convection zone (and associated surface turbulence), and hence should not have the requisite conditions for acoustically heated coronae (de Loore 1970; Renzini *et al.* 1977); for this reason alone they are discussed together here. Considering the Pointed Survey stars only, the median X-ray luminosity varies dramatically from $\sim 10^{33}$ ergs s^{-1} to $\sim 10^{28}$ ergs s^{-1} (Figs. 3*a* and 4). If we consider the f_x/f_V ratio for these stars, shown in Figure 3*b*, we note that the emission levels of the sources found in the Serendipitous and 8.5 Surveys lie well within the upper range of the Pointed Survey sources (particularly in the O star case); because the former samples are strongly biased toward brighter sources, we can thus be confident that we have observed the upper range of the true luminosity function throughout this spectral range even in the nearby sample. We note here that the OB star results first reported by Harnden *et al.* (1979*a*) and Seward *et al.* (1979), which are included here, show X-ray luminosities somewhat larger than those reported recently by Long and White (1980).

Possible correlations of X-ray emission levels with multiplicity and stellar characteristics other than spectral type have been examined and are as yet unclear. The possible effects of multiplicity upon the existence and level of X-ray emission of OB stars have been discussed by Harnden *et al.* (1979), with the conclusion that no significant effect is discernible in our data; it is not as yet possible to arrive at a similar judgment for the late B and A stars.

[10] The cutoff date for inclusion is 1979 August for all but the Pointed Survey targets, for which some data up to 1979 December have been included.

TABLE 1

X-Ray Sources Detected in the *EINSTEIN* Stellar Survey[a]

X-ray Source Name	Star Name	Optical Position R.A.	Optical Position Decl.	log F_x/F_v	log L_x (erg s^{-1})	Survey	log (ct s^{-1})
		Main Sequence - O Stars					
		h m s	° ′ ″				
1E 053249-0525.2	θ^1 Ori C	05 32 49.0	-05 25 16	-4.17	32.2	P	-0.94
1E 053255-0526.8	θ^2 Ori	05 32 55.4	-05 26 51	-4.94	31.3	P	-1.92
1E 104237-5928.4	HD 093205	10 42 37.4	-59 28 28	-3.81	33.0	P	-2.52
1E 104245-5931.0	CPD-59 2600	10 42 45.5	-59 31 08	-4.64	32.9	P	-3.0
1E 104248-5918.0	HD 093250	10 42 48.4	-59 18 07	-3.78	33.3	P	-2.4
1E 104309-5924.2	SAO 238431	10 43 09.2	-59 24 17	-4.73	...	P	-1.30
1E 2137.3+5714	HR 8281	21 37 24.3	+57 15 44	-4.2	31.9	8.5	-1.25
		Main Sequence - B Stars					
1E 0304.8+4045	β Per	03 04 54.3	+40 45 53	-4.04	30.7	P	+0.34
1E 0755.4-5251	χ Car	07 55 30.3	-52 50 30	-5.80	30.0 S	P	-1.96
		Main Sequence - A Stars					
1E 0634.8+1627	γ Gem	06 34 49.5	+16 26 36	-5.57	29.2	(E)	-1.12
1E 064255-1639.4	α C Ma A	06 42 55.3	-16 39 26	-7.60	26.9	P	-1.7
1E 110143+3830.6	51 U Ma	11 01 44.5	+38 30 40	-5.41	28.5	S	-2.89
1E 1155.4+3232	HR 4574	11 55 33.0	+32 33 09	-4.64	29.0 S	8.5	-2.00
1E 1329.9-4636	HD 117721	13 30 00.7	-46 36 16	-3.49	30.5 S	8.5	-1.48
1E 183515+3844.3	α Lyr	18 35 15.1	+38 44 18	-6.79 V	27.6 V	P	-1.89 V
		Main Sequence - F Stars					
		h m s	° ′ ″				
1E 0048.9-7125	HD 006028	00 49 01.4	-71 25 24	-3.79	29.5 S	8.5	-1.40
1E 0123.5+1854	ρ Psc	01 23 33.2	+18 54 46	-4.16	29.2	S	-1.09
1E 0124.1+3406	HD 008774	01 24 15.6	+34 07 06	-4.39	29.3 S	S	-1.68
1E 0150.2+2919	α Tri	01 50 13.5	+29 20 03	-4.31	29.5	P	-0.45
1E 0157.2-6148	α Hyi	01 57 12.8	-61 48 44	-5.91	27.9	P	-1.82
1E 0410.8+0734	46 Tau	04 10 51.3	+07 35 24	-4.22	29.1	P	-1.43
1E 0429.4+0518	HD 028736	04 29 25.1	+05 18 46	-4.39	28.9 S	8.5	-1.70
1E 0535.8-2842	ν^2 Col	05 35 47.3	-28 43 05	-4.57	28.7	8.5	-1.47
1E 1100.4+6155	HD 095638	11 00 17.1	+61 55 26	-4.00	29.1 S	8.5	-1.64
1E 1222.5+2548	HD 108102	12 22 31.8	+25 50 15	-3.23	29.9 S	8.5	-1.26
1E 1228.5+3141	HD 108944	12 28 32.3	+31 41 59	-3.92	29.0 S	S	-1.62
1E 1253.6+3835	α^1 C Vn	12 53 39.6	+38 35 00	-4.65 T	29.0 T	P	-1.66 T
	α^2 C Vn	12 53 40.8	+38 35 18	...	...	...	...
1E 1327.5-4621	SAO 224202	13 27 32.7	-46 20 33	-3.37	29.9 S	S	-1.82
1E 1335.8-2918	HR 5128	13 35 52.8	-29 18 24	-4.09	29.4 S	S	-1.20
1E 1755.8+1500	Z Her	17 55 51.2	+15 08 34	-3.27	30.3	P	-0.92

TABLE 1—*Continued*

X-ray Source Name	Star Name	Optical Position R.A.	Optical Position Decl.	log F_x/F_v	log L_x (erg s^{-1})	Survey	log (ct s^{-1})
		Main Sequence - G Stars					
		h m s	° ′ ″				
1E 0305.5+4924	ι Per	03 05 30.5	+49 25 24	-5.35	27.6	P	-1.74
1E 0834.7+6512	π^1 U Ma	08 34 46.6	+65 11 47	-3.66	29.1	S	-0.68
1E 0930.1+7002	24 U Ma	09 30 05.5	+70 03 09	-3.5	30.0	(C)	-0.16
1E 1352.3+1838	η Boo	13 52 18.0	+18 38 41	-5.54	28.0	P	-1.39
1E 143556-6037.3	α Cen A	14 35 57.0	-60 37 28	-5.62	27.1	P	-0.83
1E 1744.4+2744	μ Her	17 44 29.2	+27 44 34	-5.48 T	27.6 T	P	-1.59
1E 2003.9-6620	δ Pav	20 03 56.4	-66 19 18	-5.55	27.1	(A)	-1.74
		Main Sequence - K Stars					
1E 0330.5-0937	ε Eri	03 30 32.4	-09 37 35	-3.86	28.3	(A)	-0.12
1E 041258-0745.9	40 Eri A	04 12 53.8	-07 45 25	-1.70	27.2	P	-1.77
1E 0431.0+0516	HD 028946	04 31 11.0	+05 16 57	-4.69	27.3	8.5	-2.64
1E 1332.1-0804	EQ Vir	13 32 06.0	-08 05 09	-2.07	29.4	P	-0.58
1E 1346.7+2713	DM+27 2296	13 46 46.4	+27 13 41	-4.68 -4.50	27.0 27.0	S	... -2.19
1E 143555-6037.6	α Cen B	14 35 55.5	-60 37 47	-4.73	27.5	P	-0.49
1E 1802.9+0229	70 Oph B	18 02 56.1	+02 30 02	-3.2 T	28.4 T	(A)	-0.35 T
1E 1810.5+6940	HD 167605	18 10 21.9	+69 00 00	-2.75	29.5 S	S	-1.16
1E 2009.6+3813	HD 192020	20 09 35.7	+38 14 58	-4.00	29.0 S	8.5	-2.25
1E 2104.8+3831	61 CYG	21 04 50.5	+38 31 35	-3.8 T	27.5 T	(A)	-0.94
		Main Sequence - M Stars					
		h m s	° ′ ″				
1E 0015.6+4344	+43 44 AB	00 15 38.9	+43 44 35	-3.3 T	27.1 T	(A)	-1.34 T
1E 0136.5-1813	UV Cet L726-8	01 36 31.4	-18 12 59	-0.75 T -0.95 T	27.5 T	P	-0.70 T
1E 041258-0745.9	40 Eri BC	04 12 53.8	-07 45 25	-5.00 T	27.8 T	P	-1.25 T
1E 0539.2+1228	ROSS 47	05 39 18.0	+12 28 32	-2.43	27.1	(A)	-1.84
1E 0731.4+3158	YY Gem	07 31 25.8	+31 58 47	-1.74	29.6	S *	-0.14
1E 1053.9+0718	CN Leo	10 53 58.5	+07 17 53	-0.88	27.1	P	-1.07
1E 1103.0+4346	DM+44 2051 WX U Ma	11 02 47.5 11 02 50	+43 47 30 +43 47 10	-3.34 -1.02	27.2 27.2	(A)	-1.32 T
1E 1255.3+3529	DM+36 2322 G 164-31	12 55 17.0	+35 29 32	... -0.92 T	... 28.9 T	S ...	... -0.96
1E 1425.9-6228	Proxima Cen	14 26 03.0	-62 27 42	-1.24	27.4	(D)	-0.28
1E 1652.7-0815	WOLF 630	16 52 46.8	-08 15 09	-1.30 T	29.3 T	(A)	+0.35
1E 1744.4+2744	μ Her	17 44 29.2	+27 44 34	-5.48 T	27.6 T	P	-1.59
1E 1755.3+0438	Barnard's	17 55 21.5	+04 38 25	-3.18	26.1	P	-1.77
1E 191429+0505.5	GL 752 A	19 14 28.0	+05 05 08	-3.4	27.1	P	-1.96
1E 2226.1+5726	Kruger 60 DO Cep	22 26 10.0	+57 26 38	-2.44 T	27.4 T	(A)	-1.17 T
1E 2329.3+1939	EQ Peg A EQ Peg B	23 29 21.0	+19 39 41	-1.28 T -0.47 T	28.8 T	P	-0.20 T

* YY Gem: Serendipitous detection; target was α Gem, which was not seen. YY Gem, separation 72", was also a Columbia Astrophysical Laboratory target.

TABLE 1—*Continued*

X-ray Source Name	Star Name	Optical Position R.A.	Optical Position Decl.	log F_x/F_v	log L_x (erg s^{-1})	Survey	log (ct s^{-1})
			Giants & Supergiants - O Stars				
		h m s	° ' "				
1E 052926+0020.0	δ Ori A	05 29 27.0	-00 20 04	-4.57	32.5	P	-0.63
1E 1041.9-5917	HD 093129A	10 42 00.9	-59 17 05	-3.84	33.6	P	-2.28
1E 1042.6-5905	HD 093249	10 42 46.8	-59 05 37	-3.82	33.0	P	-1.96
1E 1043.6-5909	HD 093403	10 43 46.7	-59 08 39	-4.18	33.0	P	-1.53
1E 203035+4108.1	Cyg OB2-5	20 30 35.2	+41 08 03	-3.86	33.8	P	-2.02
1E 203122+4104.8	Cyg OB2-9	20 31 22.7	+41 04 51	-3.98	33.5	P	-2.28
1E 203127+4108.5	Cyg OB2-8A	20 31 27.1	+41 08 33	-3.2	34.3	P	-1.85
			Giants & Supergiants - B Stars				
1E 0515.1-0654	τ Ori	05 15 10.5	-06 53 49	-5.41	30.2 S	P	-1.62
1E 0533.6-0113	ε Ori	05 33 40.5	-01 13 56	-4.97	32.3	(B)	-0.42
1E 0545.4-0940	κ Ori	05 45 23.0	-09 41 09	-5.40	31.8	(B)	-0.99
1E 1758.0+0257	67 Oph	17 58 08.4	+02 55 56	-5.47	31.3	(B)	-1.82
1E 1943.4+4501	δ Cyg	19 43 24.8	+45 00 30	-5.74	29.1	P	-1.68
1E 203053+4104.2	Cyg OB2-12	20 30 53.2	+41 04 12	-4.65	34.0	P	-2.25
			Giants & Supergiants - A Stars				
1E 0850.9+1401	HD 075976	08 51 00.2	+14 01 15	-3.89	30.6 S	8.5	-1.51
1E 1732.6+1200	α Oph	17 32 36.8	+12 35 35	-5.69	28.6	P	-1.35
			Giants & Supergiants - F Stars				
1E 0622.8-5239	α Car	06 22 50.5	-52 40 03	-6.34	30.0	P	-0.82
			Giants & Supergiants - G Stars				
		h m s	° ' "				
1E 021432+5717.2	χ Per	02 14 32.2	+57 17 10	-4.58	30.3	P	-2.05
1E 051259+4556.7	α Aur	05 12 59.7	+45 56 46	-4.53	30.3	P	+0.37
1E 0526.0-2048	β Lep	05 26 06.1	-20 47 56	-5.9	29.3	P	-1.82
1E 1623.4+6137	η Dra	16 23 18.4	+61 37 38	-6.3 T	28.0 T	P	-2.15 T
			Giants & Supergiants - K Stars				
1E 1256.2+3833	DM+39 2586	12 56 14.6	+38 32 59	-2.69	31.5 S	S	-0.96
1E 1541.8+0633	α Ser	15 41 48.4	+06 34 55	-6.45	27.8	P	-2.28
1E 1646.9-3412	ε Sco	16 46 53.7	-34 12 23	-6.44	27.8	P	-2.13
			No Luminosity Class - O Stars				
1E 203120+4103.0	Cyg OB2-22	20 31 20.8	+41 03 01	-5.88	31.3	P	-2.70
1E 203135+4058.9	Cyg OB2-E	20 31 35.4	+40 58 55	...	...	P	-2.77
			No Luminosity Class - B Stars				
1E 1640.4+6225	HD 151067	16 40 32.5	+62 24 08	-4.06	...	8.5	-1.72
			No Luminosity Class - A Stars				
1E 1208.2+4009	HD 105824	12 08 16.0	+40 10 10	-4.67	...	8.5	-2.36
1E 1650.5-3020	HD 152287	16 50 31.6	-30 19 34	-3.41	...	8.5	-1.42

TABLE 1—*Continued*

X-ray Source Name	Star Name	Optical Position R.A.	Optical Position Decl.	log F_x/F_v	log L_x (erg s^{-1})	Survey	log (ct s^{-1})
			No Luminosity Class - F Stars				
		h m s	° ′ ″				
1E 0039.2+4024	HD 003914	00 39 17.5	+40 24 53	-4.82	...	8.5	-2.42
1E 0411.8+1035	HD 026781	04 11 49.2	+10 34 36	-3.93	...	S	-1.55
1E 0425.8+6456	HD 028122	04 25 49.7	+64 56 33	-4.16	...	8.5	-2.16
1E 043947-1620.5	...	04 39 47.0	-16 20 30	-2.77	...	D	-3.04
1E 0535.7-2838	HD 037484	05 35 42.0	-28 39 16	-4.25	...	8.5	-1.94
1E 0536.6-2850	HD 037627	05 36 35.9	-28 51 50	-4.16	...	8.5	-2.16
1E 110157+3830.9	HD 095976	11 01 57.2	+38 31 00	-4.01	...	S	-2.05
1E 1208.6+3924	HD 105881	12 08 38.2	+39 24 30	-4.03	...	8.5	-2.00
1E 1224.9+1001	BD+10 2425	12 25 00.7	+10 02 01	-2.97	...	S	-1.96
1E 1309.7+3221	HD 114723	13 09 41.1	+32 21 01	-4.13	...	8.5	-1.80
1E 1424.3+1638	HD 126695	14 24 21.9	+16 38 17	-3.22	...	8.5	-1.28
1E 171205+7111.8	...	17 12 05.0	+71 11 54	-3.72	...	D	-3.00
1E 171312+7111.1	SAO 008737	17 13 12.6	+71 11 07	-4.09	...	D	-2.53
1E 1742.4-2823	HD 161247	17 42 27.4	-28 23 16	-4.10	...	8.5	-2.13
1E 1743.3-2853	SAO 185730	17 43 28.3	-28 52 48	-3.10	...	S	-1.57
1E 1743.9-2809	BN Sgr	17 43 55.8	-28 07 56	-3.92	...	S	-2.38
1E 2138.7+5721	HD 206482	21 38 47.9	+57 21 15	-3.87	...	8.5	-1.54
1E 2154.9+0354	HD 208632	21 54 59.4	+03 55 09	-4.87	...	8.5	-2.44
1E 2333.9+2023	HD 221972	23 33 56.8	+20 23 20	-3.97	...	8.5	-1.85
			No Luminosity Class - G Stars				
		h m s	° ′ ″				
1E 0134.3+2027	SAO 074827	01 34 24.8	+20 26 45	-2.99	...	S	-1.33
1E 0410.0+1029	SAO 093816	04 10 02.6	+10 28 50	-3.49	...	S	-1.82
1E 0412.3+0717	SAO 111689	04 12 21.5	+07 17 24	-3.65	...	S	-1.72
1E 0429.1+6432	HD 028495	04 29 10.7	+64 31 41	-3.06	...	S	-1.13
1E 043754-1633.2	...	04 37 54.0	-16 33 12	-2.96	...	D	-3.03
1E 043838-1641.0	...	04 38 38.0	-16 41 00	-2.92	...	D	-3.00
1E 073019+6547.0	SAO 014241	07 30 19.4	+65 47 00	-3.34	...	S	-1.92
1E 0851.7+1426	HD 076081	08 51 41.2	+14 26 07	-3.57	...	8.5	-1.55
1E 1225.3+0910	SAO 119414	12 25 21.2	+09 10 30	-4.25	...	S	-2.53
1E 1226.6+3139	HD 108693	12 26 38.7	+31 40 01	-4.35	...	8.5	-2.30
1E 1330.6-0811	HD 117860	13 30 34.0	-08 11 14	-3.66	...	S	-1.33
1E 1532.9+0917	SAO 121078	15 32 55.9	+09 18 01	-3.41	...	S	-1.60
1E 1549.8+2023	SAO 084044	15 49 50.9	+20 23 50	-2.81	...	S	-1.19
1E 170606+7107.1	...	17 06 06.0	+71 07 12	-1.77	...	D	-2.95
1E 170957+7100.1	...	17 09 57.0	+71 00 06	-3.50	...	D	-3.34
1E 1854.7+0116	BD+1 3828	18 54 47.1	+01 16 31	-3.06	...	S	-1.36
1E 2203.4-0536	HD 209779	22 03 28.2	-05 36 06	-3.83	...	8.5	-1.62

TABLE 1—*Continued*

X-ray Source Name	Star Name	Optical Position R.A.	Optical Position Decl.	log F_x/F_v	log L_x (erg s^{-1})	Survey	log (ct s^{-1})
		No Luminosity Class - K Stars					
		h m s	° ′ ″				
1E 043916-1622.5	...	04 39 16.0	-16 22 30	-2.26	...	D	-3.17
1E 1053.8+0738	HD 094765	10 53 54.9	+07 39 21	-4.05	...	8.5	-1.77
1E 1238.9+1921	HD 110350	12 38 54.7	+19 20 57	-3.45	...	8.5	-1.31
1E 1527.4+1600	HD 138157	15 27 26.1	+16 21 46	-3.64	...	8.5	-1.35
1E 1615.4+3500	SAO 065201	16 15 28.6	+35 00 59	-3.51	...	S	-1.72
1E 1900.0+7037	HD 177620	18 59 58.7	+70 37 33	-3.70	...	8.5	-1.80
		Pre-Main Sequence Stars					
1E 053228-0525.1	KM Ori	05 32 28.3	-05 25 07	-2.30	30.9	S	-2.17
1E 053250-0524.6	MT Ori	05 32 50.3	-05 24 38	-2.45	31.1	S	-2.00
1E 053256-0532.6	V358 Ori	05 32 56.2	-05 32 38	-2.38	30.8	S	-2.25
1E 053314-0530.0	AN Ori	05 33 14.2	-05 30 04	-2.58	31.0	S	-2.05
		Dwarf Novae					
1E 0752.1+2208	U Gem	07 52 07.8	+22 08 09	-0.54	30.1	P	
1E 1815.0+4948	AM Her	18 15 00	+49 48 00	+1.1	32.6	P	
1E 2140.7+4321	SS Cyg	21 40 44.4	+43 21 22	+0.23	32.2	P	

U Gem: 0.5 - 4.5 keV (IPC), low state
AM Her: 0.1 - 3.5 keV (OGS+MPC), high state (normal)
SS Cyg: 0.4 - 6 keV (OGS+MPC;IPC), low state

X-ray Source Name	Star Name	Optical Position R.A.	Optical Position Decl.	log F_x/F_v	log L_x (erg s^{-1})	Survey	log (ct s^{-1})
		White Dwarf Detections					
		h m s	° ′ ″				
1E 064255-1639.3	α C Ma B	06 42 55.9	-16 39 19	-1.21	28.8	P	+0.24
1E 131400+2921.7	HZ 43	13 14 00.3	+29 21 47	+0.60 T	31.6 T	P	+0.46
		Other Stars					
		h m s	° ′ ″				
1E 104306-5925.2	η Car	10 43 06.8	-59 25 15	-3.47	33.5	P	-1.30
1E 1458.2-4122	SAO 225377	14 58 15.1	-41 22 15	-3.59	...	S	-1.96
1E 203043+4103.9	Cyg OB2-C2	20 30 43.1	+41 03 55	...	32.5	P	-2.38

[a] The table includes all detections and corresponding optical counterparts of the survey programs described in § II, as well as of collaborating guest investigators, sorted by stellar type and Right Ascension. The particular program or observer is identified under the "Survey" heading (P: pointed survey, 8.5: V=8.5 magnitude-limited survey, S: serendipitous survey, D: deep stellar survey). The focal plane instrument used for primary detection is specified by the precision of the Einstein source name identification (HRI sources have five significant digits in the Declination identifier; see § II in text).

Guest observers (in "Survey" column):

(A) H. Johnson
(B) J. Cassinelli
(C) C. Zwaan & R. Mewe
(D) B. Haisch & J. Linsky
(E) A. Fabian, Inst. of Astron., Cambridge, U. K.

L_x: Letter "S" after luminosity indicates that the distance was determined by spectroscopic parallax

L_x or F_x/F_v: Letter "T" after value indicates that the total X-ray flux is used (assigned to indicated component for F_x/F_v)

Letter "V" after an entry indicates X-ray variability.

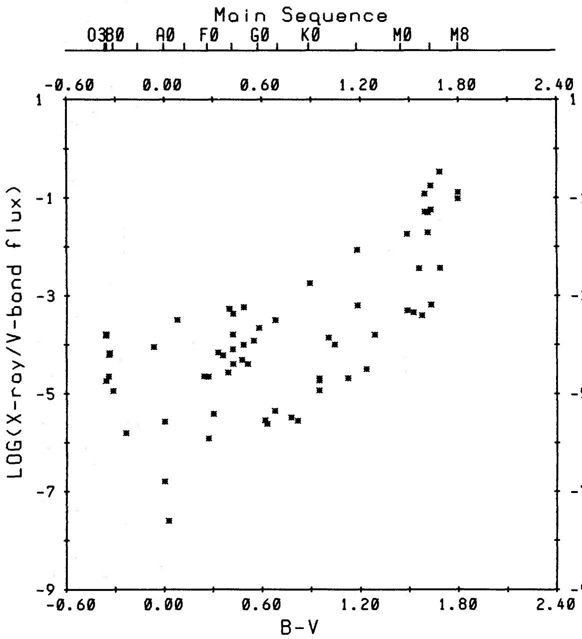

FIG. 2*a*

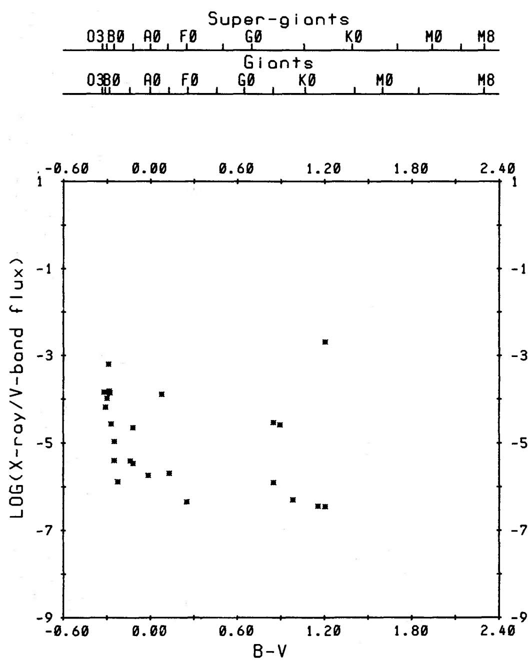

FIG. 2*b*

FIG. 2.—The ratio of soft X-ray to *V*-band fluxes for stars detected in the Survey; stars are divided into: (*a*) main sequence (luminosity classes IV, V, and VI); (*b*) giants and supergiants (luminosity classes I, II, and III), and (*c*) stars whose luminosity class has not as yet been determined. In order to compare the latter group with the others, we have used *V*-band fluxes, which are readily available, rather than bolometric fluxes which cannot be calculated for group (*c*).

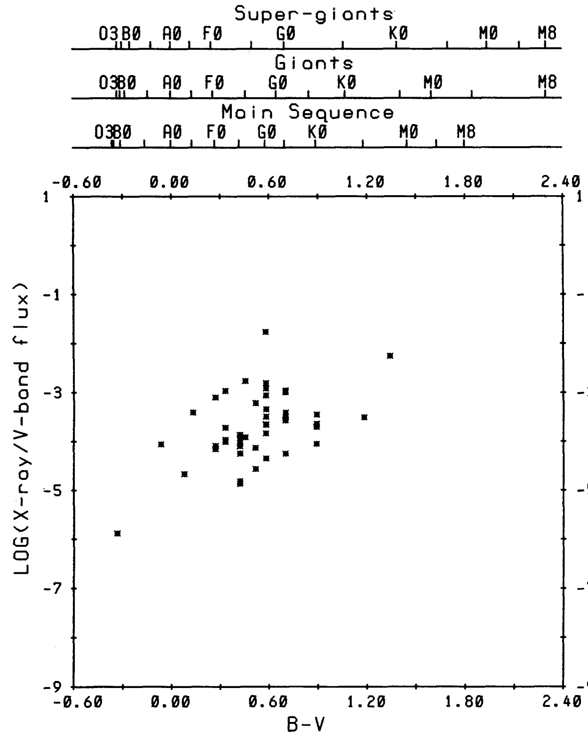

FIG. 2*c*

b) *Late Type* (*F, G, K, M*) *Main-Sequence Stars*

i) *F Stars*

The nearby sample of optically well-characterized dF stars shows them to be clustered about an X-ray luminosity of $\sim 10^{29}$ ergs s^{-1} (Fig. 3*a*), corresponding to an f_x/f_V ratio of $\sim 10^{-4.5}$ (Fig. 3*b*). F stars from the Serendipitous and 8.5 Surveys, in which F stars are the dominant stellar type detected, have an f_x/f_V ratio distribution which overlaps that of the nearby (Pointed Survey) sample, but with a bias toward somewhat larger levels of X-ray emission. The substantial overlap in the two distributions suggests that the stars of these two surveys are dominantly the same as those of the Pointed Survey, i.e., main-sequence stars. This possibility is consistent with the frequency distribution of the observed sources as a function of *V*-band magnitude; that is, the optically fainter stars are systematically intrinsically brighter in X-rays, as would be expected if we are seeing the upper range of the true dF X-ray luminosity distribution as we look at optically fainter main-sequence stars. Furthermore, although the number of dF stars per $(1°)^2$ in a random field is still increasing at $V = 8.5$ (Allen 1973), the actual number of detected X-ray sources drops dramatically above this limiting magnitude, consistent with "running out" of sources for exposures with an average limiting sensitivity of $\sim 10^{-13}$ ergs cm^{-2} s^{-1} at Earth. The brightest sources in the 8.5 Survey therefore represent the brightest sources of the dF luminosity function.

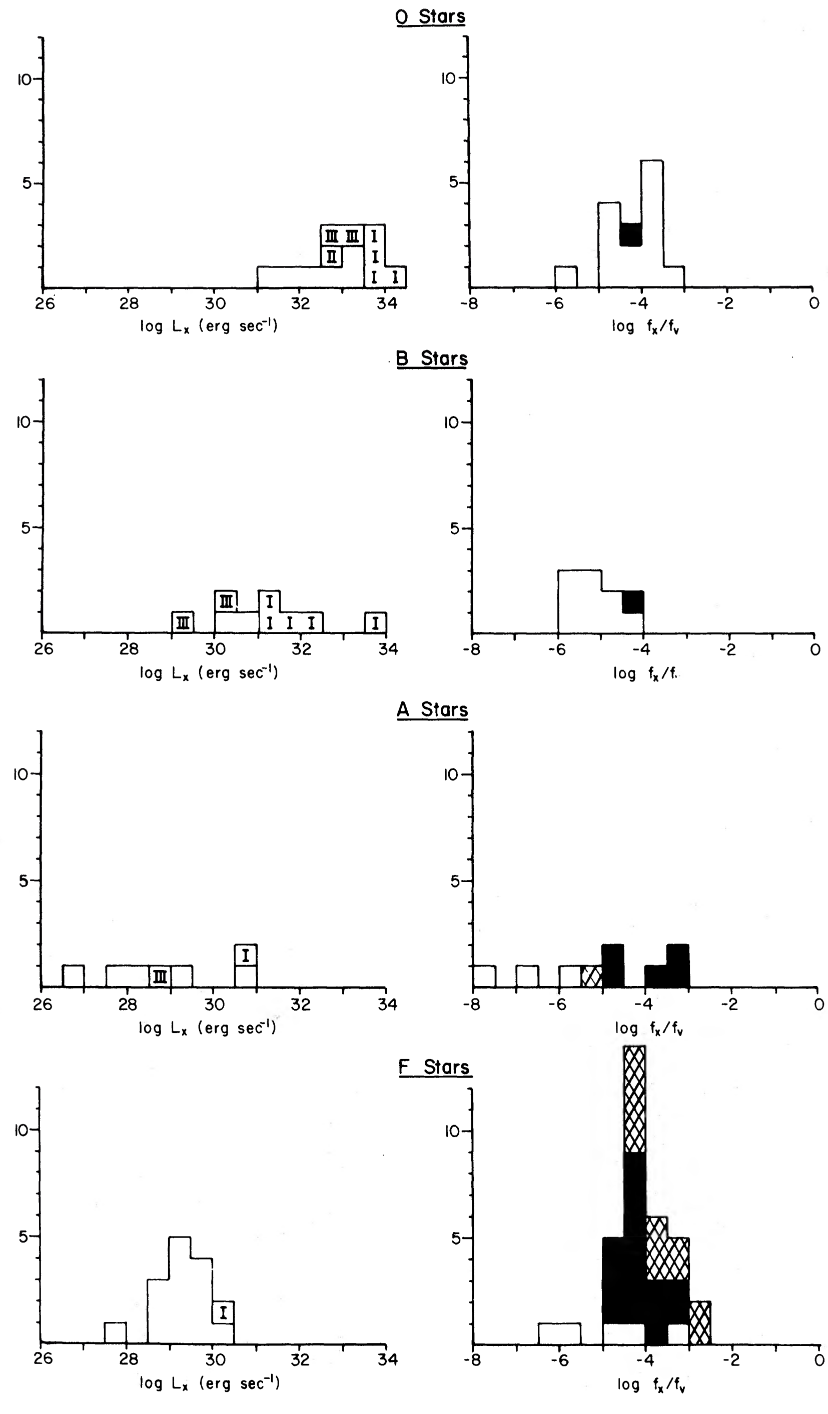

FIG. 3.—(*a*) *Left-hand columns:* histograms showing the distributions of X-ray luminosities L_x for stars of spectral type O through M; labels I, II, III indicate those luminosity classes and blanks indicate main-sequence stars (IV, V, or VI). (*b*) *Right-hand column:* histograms showing the distribution of the ratio X-ray flux/*V*-band flux f_x/f_V for the stars of Fig. 3*a*, but including also those stars whose luminosity classes are not known. The histograms are subdivided according to the surveys which yielded the data; blank indicates Pointed Survey, black indicates 8.5 Survey, and crosshatch indicates Serendipitous Survey (see § II for descriptions of the various surveys). Also indicated for G stars are the f_x/f_V ratios which would be seen if the Sun's corona consisted entirely of coronal holes (CH), quiet corona (QS), active regions (AR), or X-ray flares (F), respectively.

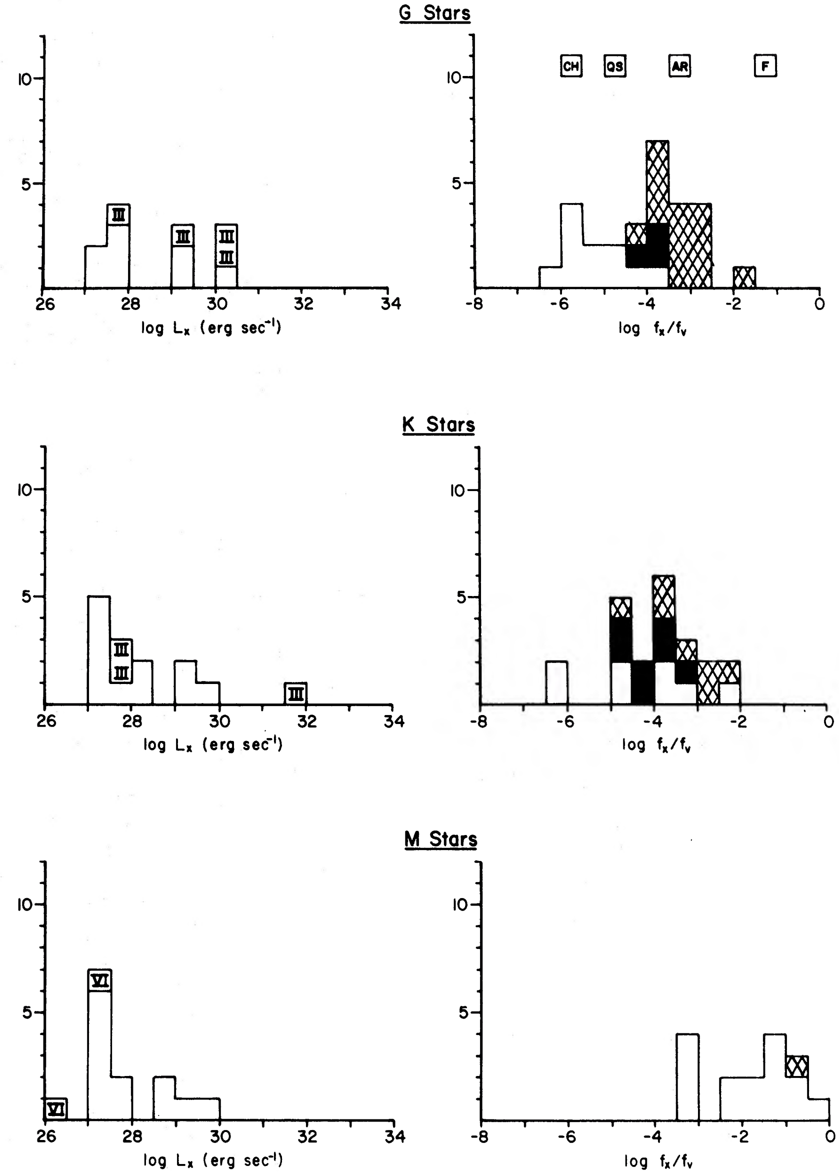

FIG. 3—*Continued*

Here we note that the RS CVn stars in our sample, which we have chosen not to segregate, show emission levels comparable to the brightest of the non–RS CVn stars (either F, G, or K).

ii) *G Stars*

The nearby (Pointed Survey) G stars show a fairly wide range of emission levels which, if combined with the known level of solar soft X-ray emission levels (see Vaiana and Rosner 1978), spans over four orders of magnitude; the X-ray luminosity ranges from $\sim 10^{26}$ ergs s^{-1} to $\sim 10^{30}$ ergs s^{-1}, with corresponding f_x/f_V values ranging from $10^{-6.5}$ to $-10^{-3.6}$. The optically unclassified G stars of the 8.5 and Serendipitous surveys have characteristics similar to those of the F stars of the same surveys: they are uniformly fainter optically and tend to be intrinsically brighter in X-rays than G stars of the nearby sample (Fig. 3). Study of the proper motions of 8.5 survey stars shows that, under the assumption that they are giants, a means space velocity in excess of 100 km s^{-1} is obtained; under the assumption that they are dwarfs, a mean space velocity of ~ 10 km s^{-1} is obtained (Topka 1980). As the latter result is far more plausible (cf. Allen 1973), the presumption is therefore very strong that—as in the case of F stars—the optically unclassified sample consists dominantly of dwarfs.

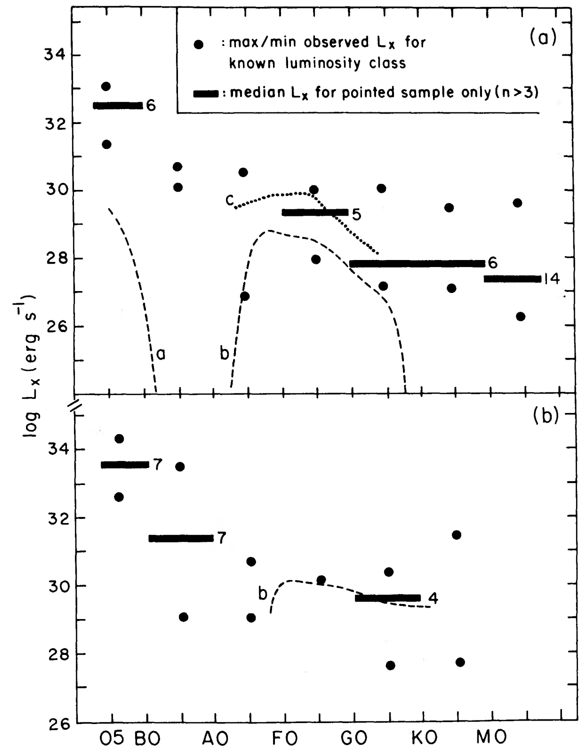

FIG. 4.—Variation in X-ray luminosity L_x *vs.* spectral type for the optically well-classified sample of stars: (*a*) main sequence, (*b*) giants and supergiants. We indicate, by means of circles, the maximum and minimum value of L_x found in this optically well-classified sample (which is by no means statistically complete) and, by means of horizontal bars, the median value of L_x for the subset of Pointed-survey stars (see § II). The median has been calculated only if this subsample contains more than three stars for a given spectral type; we indicate, by a small numeral adjacent to each bar, the number of stars which entered into the median computation. For comparison we also plot several theoretical predictions of X-ray emission levels, all based upon acoustic coronal heating [(*a*) and (*b*) from Mewe 1979; (*c*) from Landini and Monsignori-Fossi 1973; see text for discussion of passbands]. Our primary intention here is to emphasize the gross discrepancies between such theories and observation of the present (statistically incomplete) sample at early and late spectral types.

In spite of the wide range of X-ray emission levels of dG stars, there appears to be evidence that the true luminosity function does change as one goes from F to G stars. This tentative conclusion rests upon the observation that the X-ray luminosity functions of nearby dF and dG stars peak at distinctly different luminosity values (even though they were observed with comparable sensitivities; cf. Fig. 3), and cannot be due to a magnitude-dependent selection effect since the optical magnitude distribution of the two samples is similar; this conclusion is supported by a statistical analysis of the 8.5 Survey results (Topka 1980; Topka *et al.* 1979). It appears that the true X-ray luminosity function of dG stars extends to significantly lower luminosities than that of the dF stars.

Finally, we note that a possible hint to the underlying cause responsible for the broad spread in dG X-ray emission levels (as well as in that of late type dwarfs in general) is contained in the fact that the brightest dwarf (π^1 UMa) is a rapidly rotating, single star with a very active chromosphere (cf. Smith 1978; Linsky *et al.* 1979). In contrast, the relatively weakly emitting Sun and α Cen A are fairly slow rotators, with comparatively inactive chromospheres (Ayres and Linsky 1980*a*). This association between rapid rotation and high X-ray emission levels for the *Einstein* sample of stars persists throughout the spectral range later than G (Vaiana 1980); a similar result for earlier spectral types has not been established. This effect may account for the skew of the dG X-ray luminosity distribution, relative to that of the dF stars, toward lower emission levels (because F dwarfs have, as a class, larger mean rotation rates than G and later dwarfs; see Tassoul 1978 for review and references).

iii) *K Stars*

In the Pointed Survey, dK stars show a typically broad range of emission levels, with L_x ranging from $\sim 10^{27}$ ergs s^{-1} to $\sim 10^{29}$ ergs s^{-1} (Fig. 3*a*) and f_x/f_V ranging from $\sim 10^{-5}$ to $\sim 10^{-2}$ (Fig. 3*b*). A number of K stars were identified as sources in the Serendipitous and 8.5 Surveys, with emission levels comparable to that found in the nearby sample. Although one expects K giants to be far more numerous than K dwarfs at a limiting magnitude of $V = 8.5$ (Allen 1973), our X-ray data on nearby gK stars (see below)—showing a somewhat lower f_x/f_V ratio for giants—suggest that the stars seen in the Serendipitous and 8.5 Surveys are dominantly dwarfs. This suggestion is supported by the Deep Survey observations of a $V = 14.6$ K8–9 star, with $f_x/f_V \sim 10^{-2.5}$; at $V \sim 14.6$, one expects roughly three dwarfs and essentially no giants to fall within a ($1° \times 1°$) optical field at high galactic latitudes ($\gtrsim 30°$), so that the observed star is in all probability a dwarf.

Comparison of X-ray emission levels with other stellar characteristics suggests that—as for dG stars—(i) the strength of emission lines such as Ca II H and K correlates with X-ray intensity (viz., α Cen B and DM +272296 versus ϵ Eri and EQ Vir; also see Mewe and Zwaan 1980); (ii) rotation may be an important determinant of activity level (Vaiana 1980; cf. EQ Vir, which is known to be a rapid rotator [Anderson, Schiffer, and Bopp 1977] and is the X-ray brightest dK star). We note that the high fraction of multiple star systems in the dK sample makes it difficult to uniquely assign emission levels to the various components; for the nearest systems (viz., α Cen A, B), the HRI can resolve the individual components (Golub *et al.* 1979) and has been and will continue to be used to resolve this problem whenever possible.

iv) *M Stars*

The most striking result of observations of dM stars is that *all* show emission levels comparable to that of earlier spectral type dwarfs, with L_x ranging from $\sim 10^{26}$ ergs s^{-1} to $\sim 10^{29}$ ergs s^{-1} (Fig. 3*a*), corresponding to f_x/f_V ranging from $\sim 10^{-3}$ to $\sim 10^{-0.7}$ (Fig. 3*b*). Because of their intrinsic faintness, dM stars with $V < 8.5$ are extremely rare; it is hence not surprising that none were found in the 8.5 survey. However, extrapolating these observations to exposures with highest sensitivity, one would expect to detect a significant number of dM stars as X-ray sources in deep survey fields, with optical counterparts whose V magnitude exceeds ~ 20 (Rosner *et al.* 1979*a*); the observations are as yet inconclusive on this point.

There is some evidence in the data that the level of X-ray emission for dM stars, as for the other late-type dwarfs, correlates with: (i) multiplicity (and hence, for close binaries, with rotation) and (ii) emission-line behavior (Rosner *et al.* 1979*a*). Thus the least luminous sources (e.g., CN Leo and Barnard's star) are the only unambiguously single stars in our sample. Similarly, the X-ray brightest stars tend to be classified as active stars in general (e.g., as dMe, spot, and/or flare stars; viz., YY Gem, EQ Peg), whereas the weakest X-ray emitting stars tend toward less dramatic activity (viz., Barnard's star).

v) *Summary for Late Type Dwarfs*

We conclude that, if one examines the data for dwarf stars later than F in toto, a remarkable similarity in X-ray properties emerges: the median X-ray emission levels of the Pointed sample, as well as the range of emission levels of all optically well classified stars, change relatively little as the spectral type varies from G to late M. Since the stellar surface area experiences a drastic reduction in this spectral range (an almost 100-fold change), these stars seem to obey a kind of total X-ray flux conservation law, such that the average X-ray surface brightness increases as the stellar radius decreases. The major change in X-ray luminosity for these types of stars appears to occur at the dF/dG spectral type boundary; this change (a skewing of the X-ray luminosity function to lower emission levels) coincides roughly with the sharp decrease in mean rotation rates of field stars observed in this spectral type range.

c) *Evolved Stars*

i) *Early Type Giants and Supergiants*

The relatively large number of evolved early-type stars found to be soft X-ray sources by the *Einstein* stellar survey (Fig. 1, Table 1), as is the case for their main-sequence counterparts, is primarily a reflection of their strong spatial correlation: the discovery that stars in OB associations are indeed X-ray sources Harnden *et al.* 1979*b*; Seward *et al.* 1979; Long and White 1980) ensured that many such stars would be observed.

Examination of the observed X-ray luminosity distribution of these stars (Fig. 3) shows that: (*a*) O giants and supergiants have high emission levels, somewhat in excess of those of main-sequence stars of the same spectral type and consistent with the proportionality between X-ray and visual luminosity reported by Harnden *et al.* (1979*a*, *b*; see also Rosner *et al.* 1979*b*; Cassinelli *et al.* 1979; Long and White 1980); (*b*) B and A spectral type evolved stars have distinctly lower emission levels than O giants and supergiants, thus showing the same behavior with spectral type as their dwarf counterparts.

ii) *Late Type Giants and Supergiants*

The Pointed Survey has detected one F supergiant, four G giants, and two K giants (Table 1). We have also looked at K and M giants and M supergiants, but have thus far obtained only upper limits; there is some support, therefore, for the suggestion that there is decreasing prevalance of hot coronae toward evolved stars of later spectral type (Linsky and Haisch 1979).

The detections show these late-type evolved stars to be very modest soft X-ray sources if their X-ray emission is compared to their optical output (or if their mean surface X-ray flux is computed), with $f_x/f_V \lesssim 10^{-5}$; for example, the corresponding surface flux for Canopus (F0 I) is comparable to solar coronal hole values. The two exceptions (Capella and Algol) are complex multiple-component systems for which unique assignment of emission levels is not possible. We note, however, that the total X-ray luminosity of the detected sources can be substantial; the F supergiant Canopus, for example, is as bright in X-rays as the brightest of the single late-type main-sequence stars.

Perhaps most striking of our observations of these stars are the strong upper bounds upon the mean surface flux we can place upon some very late giants and supergiants. We have upper bounds for ϵ Sco (K2 III–IV; $f_x/f_V \lesssim 10^{-6.6}$), β Peg (M2 II; $f_x/f_V \lesssim 10^{-5.9}$), α Ori (M2 Iab; $f_x/f_V \lesssim 10^{-6.8}$) and α Sco (M1 Ib, $f_x/f_V \lesssim 10^{-7.1}$). For α Sco the corresponding upper bound upon the mean X-ray surface flux is $\sim 10^{0.9}$ ergs cm^{-2} s^{-1}, characteristic of solar coronal holes (Maxson and Vaiana 1977), the least active portion of the solar corona. Any corona on α Sco must be rather feeble; but because inhomogeneity cannot be excluded, it is still possible for α Sco to have significant *localized* coronal emission, that is, the upper bound upon its total X-ray luminosity is $10^{29.3}$ ergs s^{-1}, quite comparable to that of the brighter late-type dwarfs. In summary, our data indicate that the X-ray surface flux (but not the luminosity) varies with effective gravity, with late supergiants consistently showing the lowest surface fluxes (or upper bounds) at any given spectral type.

d) *Pre–Main-Sequence Stars*

Early *Einstein* IPC observations of the Orion complex strongly suggested that pre–main-sequence stars are also soft X-ray sources (Ku and Chanan 1979). These observations have been confirmed by extensive HRI observations reported by Chanan *et al.* (1979) and by early HRI observations carried out as part of the present survey and reported here; the much higher spatial resolution of the HRI leaves no doubt as to the optical identification (see the four sources listed in Table 1). The sources observed in the CfA pointing, corresponding in the optical to Orion nebular variables (Kukarkin 1968), have relatively large values of f_x/f_V, lying at the upper range of f_x/f_V ratios observed for main-sequence stars of similar spectral type. For an assumed distance of 400 pc, these sources have an X-ray luminosity of $\sim 10^{30.6}$–$10^{30.9}$ ergs s^{-1}. Our survey of main-sequence stars reveals only one single late-type star (24 UMa) with comparable luminosity; 24 UMa is a giant-subgiant chosen because of its high Ca II emission (see Table 1).

We caution that the above narrow range of inferred luminosities for these young stars is in all probability a selection effect. We have obtained a number of upper limits at the emission level of the weakest detected source. However, Chanan *et al.* (1979) have reported a far larger number of detections, based on much more extensive observations than reported here. The implication is that the limiting sensitivity of our shorter HRI observation allowed only a small number (e.g., the brightest) of the Orion nebular variables in the field to be seen.

e) *White Dwarfs*

Because of the intrinsic optical faintness of white dwarfs, the 8.5 Surveys could not reasonably be expected to supplement our Pointed observations of the nearest such stars. Instead, a computer-based catalog of white dwarfs was used to search all IPC Survey fields for X-ray emission from white dwarfs falling serendipitously into these fields (Topka *et al.* 1979). The catalogs upon which this search was based were copies of those due to Luyten (1969) and Gliese (1969), which are not in any sense magnitude-limited;[11] at present we do not regard this search for serendipitous white dwarf X-ray sources as statistically complete. Our search provided upper bounds for 34 white dwarfs: none was detected as an X-ray source in the CfA survey (see Table 2).

The white dwarf portion of the Pointed Survey has been similarly unfruitful, pointing at 11 white dwarfs, and detecting only the two previously known sources, HZ 43 (Hearn *et al.* 1976; Lampton *et al.* 1976; Heise and Huizenga 1980) and Sirius (Mewe *et al.* 1975). In the second case, however, our HRI observation definitively resolves the question of which component of the Sirius system is the emitter: *both* Sirius A and B are X-ray sources, the white dwarf being by far the *dominant* contributor to the total system X-ray flux. We note that because the Pointed Survey concentrated upon nearby white dwarfs, the stronger (relative to the Serendipitous results) upper bounds obtained are to be expected (Table 2).

Considering our white dwarf data (detections and upper bounds) *in toto*, several results emerge. First, a substantial number of our upper bounds fall below the flux values derived for the detected sources. Comparing Tables 1 and 2, we see that a number of nearby white dwarfs have upper bounds on L_x at or below the weakest detected white dwarf (Sirius B, $L_x \sim 10^{28.8}$ ergs s^{-1}). We are therefore forced to conclude that *if* white dwarfs constitute a class of X-ray sources, their X-ray luminosity distribution must be broad and their median luminosity far below our detection levels.

A second striking characteristic is that the detected white dwarfs have large X-ray to optical emission ratios with values of f_x/f_V in excess of the values attained by any of the nondegenerate stars. Under the assumption that the X-ray emitting volume overlies the white dwarf surface (as in a coronal model), we have computed the mean surface X-ray flux $\mathscr{F}_x$ for these stars, and find that it is many orders of magnitude in excess of that observed for any nondegenerate star. For example, we compute an $\mathscr{F}_x \sim 10^{10}$ ergs cm^{-2} s^{-1} for Sirius B, assuming its radius to be $\sim 10^{-2}\ R_{\odot}$; to place this figure in perspective, the mean solar surface X-ray flux under the assumption that the entire solar surface is covered by small (C) flares would be $\sim 3 \times 10^8$ ergs cm^{-2} s^{-1} (Vaiana and Rosner 1978). If coronal, the process leading to X-ray emission from these white dwarfs would then be indeed spectacular; the extremely large value of $\mathscr{F}_x$ in fact casts some doubt upon a simple coronal interpretation, and the relatively low estimated effective temperature of Sirius B seems to exclude the possibility of direct (thermal) surface emission. This suggests that in this case the X-ray source surface area is substantially larger than the white dwarf surface area (as would be the case if the emission derived from an accretion disk).

f) *Cataclysmic Variables*

Cataclysmic variables have long been considered to be a separate class of objects (at least as far as X-ray emission is concerned) from the "normal" stars; we have included them here for the sake of completeness from the point of view of low-luminosity galactic X-ray sources. If, as is presently believed, the main source of energy in these systems is the release of the gravitational energy of the matter onto the white dwarf and an accretion disk, they are quite different from the other stellar systems discussed in the present survey paper.

As part of the CfA program, we have looked at three such objects: U Gem, SS Cyg, and AM Her. The results of a detailed study of *Einstein*, *IUE*, and optical simultaneous observations and their implications for the model of these systems are reported by Fabbiano *et al.* (1980); here we note that their X-ray luminosity is of the order of 10^{30}–10^{32} ergs s^{-1}, with $f_x/f_V \sim 10^{-0.5}$–$10^{1.1}$. This places them at the upper end of the late type star X-ray luminosity distribution and at the extreme upper end of the f_x/f_V distribution for all stellar systems. We note that the values of L_x and f_x/f_V determined for U Gem, SS Cyg, and AM Her are similar to those of HZ 43 and Sirius, both binary systems containing a white dwarf (see Margon *et al.* 1976 for discussions of binary nature of HZ 43); it should be noted, however, that the spectral characteristics of the latter two sources differ substantially from those of the cataclysmic variables.

IV. DISCUSSION

Our fundamental conclusion, only partially illustrated by Figure 4, is that *stars in general—virtually irrespective of spectral type, luminosity class, age, or any other distingu-*

[11] As pointed out by Gliese (1969), the catalog also contains high-velocity dM and other stars; it therefore provides an additional means of searching for serendipitous X-ray sources associated with nondegenerate stars fainter than $V = 8.5$, but not in any statistically complete sense.

TABLE 2A

SELECTED UPPER LIMITS[a]

Star Name	Spectral Type	Visual Magnitude	Upper Limit log F_X/F_V	Upper Limit log L_X (erg s^{-1})	Survey
66 Oph	B2 Ve	4.84	-5.2	30.6 S	P
HR 2142	B2 IV-Vne	5.23	-5.2	30.7 S	P
139 Tau	B1 Ib	4.78	-5.3	31.7 S	(B)
o^2 C Ma	B3 Ia	3.04	-6.1	31.2 S	(B)
56 Ari	Ap	5.60	-5.07	29.3	P
o Vir	A2p	4.93	-5.15	29.1	P
γ Tra	A0 Vp	2.89	-6.42	28.1	P
HD 014590	Am	5.46	-5.11	28.7 S	8.5
HD 255690	A1m	6.86	-4.26	30.0 S	8.5
ζ U Ma	A2 V + Am	3.96 V	-5.56	28.3	P
78 Vir	Ap	4.94	-5.3	28.5 S	P
α Lyr *	A0 V	0.04	-7.4 *	27.0 *	P
τ Cet	G8 VI	3.50	-5.8	26.8	(A)
82 Eri	G5 V	4.26	-5.6	27.0	(A)
α Ari	K2 III	2.00	-6.7	27.8	P
α U Ma	K0 II-III	1.80	-6.6	28.3	P
α Ori	M2 Iab	0.80	-6.8	30.2	P
α Sco	M1 Ib	1.08	-7.1	29.4	P
β Peg	M2 II	2.56	-5.9	29.3	P

[a] Ordered by spectral type; limits selected to include only those which add significant information to Table 1.

* α Lyr, though not seen with the IPC, was detected with the HRI (see Table 1).

TABLE 2B

WHITE DWARF UPPER LIMITS[b]

Star Name	Spectral Type	Visual Magnitude	Upper Limit log F_X/F_V	Upper Limit log L_X (erg s^{-1})	Survey
GR 267	DA	15.0	-0.96	28.9	P
EG 005	DG	12.37	-2.38	26.5	P
EG 011	DA	12.84	-2.17	27.7	P
EG 248	DG	14.60	-1.42	27.4	P
EG 046	DA?	12.9	-2.08	28.3	P
EG 054	DF + M	13.00	-2.35	26.8	P
EG 099	DA	12.31	-2.23	27.9	P
EG 100	DK	14.71	-1.33	27.1	P
GR 372	DKp?	14.15	-1.58	26.9	P
EG 129	DA	13.18	-2.11	27.6	P
EG 131	DA +dM5	12.36 12.75	-2.36 -2.21	27.3	P
EG 144	DA	12.88	-2.17	27.9	P
ROSS 627	DF	14.24	-2.25	27.5	S
BPM 94172	DA	13.01	-2.33	27.3	S
LP 658-2	DK	14.52	-1.52	26.8	(A)

[b] Only the most significant white dwarf upper limits are given. Less significant values also exist for a number of other white dwarfs.

Guest observers (in "Survey" column):

(A) H. M. Johnson
(B) J. Cassinelli

ishing feature—constitute a class of X-ray sources; only a few types of stars have not as yet been detected as X-ray sources (very late giants and late-type supergiants), and for these the upper bounds on luminosity are relatively high. Much of the evidence for this conclusion is schematically summarized by the curves in Figure 4, which show the variation of the median observed soft X-ray luminosity L_x with spectral type for main sequence, giant, and supergiant stars, thus also displaying the variation of L_x with effective gravity for fixed spectral type. In the present section, we address the questions of the source of this X-ray emission and its pervasiveness.

a) "*Coronal*" *versus Alternative Interpretations*

A number of mechanisms have been proposed to account for possible X-ray emission associated with *particular* types of stars; these processes can involve local plasma heating in the vicinity of the stellar surface (the "coronal model" [de Loore 1970; Renzini *et al.* 1977; Landini and Monsignori-Fossi 1973; Hearn 1975; Mullan 1976; Cassinelli and Olsen 1978; Thomas 1975; Bisnovatyi-Kogan and Lamzin 1979; Rosner and Vaiana 1979; Lucy and White 1980]), plasma heating via mass accretion (Gorenstein and Tucker 1976 and references therein), or shocking of strong stellar winds (Weaver *et al.* 1977; Cooke, Fabian, and Pringle 1978); the latter two processes have received particular attention in the context of X-ray emission from early-type stars.

Consider first the early-type stars. The initial *Einstein* data on X-ray emission from early-type (OB) stars in Cygnus OB2 and η Car, which first established such stars as a distinct class of low-luminosity X-ray sources (Harnden *et al.* 1979*a*; Seward *et al.* 1979; see also Cassinelli *et al.* 1979; Harnden *et al.* 1979*b*; Stewart *et al.* 1979; Long and White 1980), provide strong evidence for a "coronal" interpretation alone. A significant aspect of the argument presented by Harnden *et al.* was the demonstration that X-ray emission properties were not strongly dependent upon the characteristics of the O star involved, other than through its optical luminosity[12] (also Rosner *et al.* 1979*b* and Long and White 1980); in particular the presence of binary components does not appear to be an essential element in determining the existence of X-ray emitting plasma. A comparable argument can be advanced against models which involve wind collision with the interstellar medium (which are most strongly excluded by source temperatures and the absence of spatial source extension in HRI images; see Harnden *et al.* 1979*a*, *b*), contrary to the conclusions of Ku and Chanan (1979).

These arguments remain in force over the entire H-R diagram: that is, examination of Table 1 shows no correlation between *existence* of stellar X-ray emission and existence of binary components,[13] and HRI images of the nearest stars give no evidence for source extension. This, of course, does not mean that X-ray producing processes unique to binary or multiple star systems are not operative in some cases and that for particular systems (viz., compact close binaries, dwarf novae) such processes cannot dominate "coronal" processes, and also lead to the existence of hot plasma. Nevertheless, we conclude that the pervasive nature of X-ray emission is in all probability due to the presence of *coronae as a general stellar phenomenon*, with other processes playing a dominant role only in rare instances. The *Einstein* Stellar Survey has therefore settled in the negative—on the basis of direct observations—the long-debated question of whether stellar coronae were characteristic *only* of a restricted class of late-type stars.

b) *Comparison of Data with Standard Coronal Models*

If we accept the above argument on the coronal origin of most of the observed stellar X-ray emission, we may ask whether the data presented here—which for the first time display X-ray emission levels throughout the H-R diagram—are in accord with published models of stellar coronal emission. We focus upon three representative such theories: those of Landini and Monsignori-Fossi (1973), Gorenstein and Tucker 1976), and Mewe (1979); the latter is an application and refinement of Hearn's (1975) minimum flux coronal theory (see also Mullan 1976). These three models assume that coronal heating is due to the shock dissipation of a uniform flux of acoustic modes,[14] that the hot coronal plasma responsible for the observed emission is constrained from escape only by stellar gravity, and that the mean coronal radiative loss for a given star can meaningfully be represented by calculations based upon homogeneous model atmospheres.

These assumptions can be tested for the solar corona where, unlike stellar coronae, the X-ray emitting plasma can be spatially resolved. However, none of these three assumptions can be easily reconciled even with solar coronal observations (see reviews by Vaiana and Rosner 1978; and Wentzel 1978). In order to test whether the above models, together with the underlying assumptions, gain any credence in the more general stellar context, we have plotted as a function of spectral type for all three models the predicted X-ray luminosity L_x in Figure 4.[15]

[12] Note that the particular dependence upon optical luminosity found by Harnden *et al.* obtains *only* for early-type stars.

[13] On the other hand, the *level* of X-ray emission may well depend strongly upon the presence or absence of binary components, viz., RS CVn stars (Walter *et al.* 1980*a*) and dM stars (§ III above), presumably because of tidal coupling and enhanced stellar rotation rates in close binaries (cf. Tassoul 1978).

[14] Note, however, that in Hearn's (1975) formulation, no specific heating process is assumed.

[15] The instrumental passbands used in these predictions differ somewhat from that of *Einstein*; a detailed analysis of thermal spectra shows, however, that these predicted luminosities require relatively little correction (generally less than 0.5 in the log) in order to allow meaningful comparison with the observed values of L_x (shown in Fig. 4) over the temperature range $10^6 < T < 10^7$ K.

The comparison is dominated by two striking contradictions. First, stars of late B and early A spectral type as well as a subset of late-type stars (late F to early G) have levels of X-ray emission substantially, or even many orders of magnitude, in excess of predictions. Second, dwarf stars later than ~ G5 remain at a luminosity level of log $L_x \sim 28 \pm 1.5$ with increasing $B - V$, completely in conflict with the theoretical expectation that L_x should steeply decrease with increasing $B - V$. The only (qualitative) correspondence between theory and data occurs in a narrow spectral range from late A to early G for main-sequence stars, but even here the broad range of emission levels encountered remains unexplained.

Some of these results confirm early studies which noted the need for revising standard coronal theories.[16] The key difficulties can be brought into sharper focus by comparing the theoretically predicted acoustic wave flux f_a (ergs cm^{-2} s^{-1}) available to heat the corona above the stellar surface with the X-ray surface flux f_x (ergs cm^{-2} s^{-1}) derived from our data; such a comparison is presented in Figure 5 and reveals two distinct facets of contradiction.

i) There is a *quantitative* discrepancy between the calculated mechanical wave flux available for coronal heating and the observed X-ray flux. Although uncertainties in the theory (due to difficulties in theories for convection, sound generation in a turbulently convective fluid, and the thermalization of acoustic flux) may account for some of the discrepancies (see Jordan 1973 and Toomre *et al.* 1976), cases such as early A dwarfs and late-type dwarfs require corrections of many orders of magnitude; it seems unlikely that the *quantitative* differences can be resolved by considering more sophisticated acoustic heating theories in the context of revised convection theories and acoustic conversion and propagation models.

ii) There is a *qualitative* discrepancy between the observed functional dependence of X-ray flux on spectral type and the theoretical predictions. This discrepancy manifests itself in two ways. There is a large spread in the

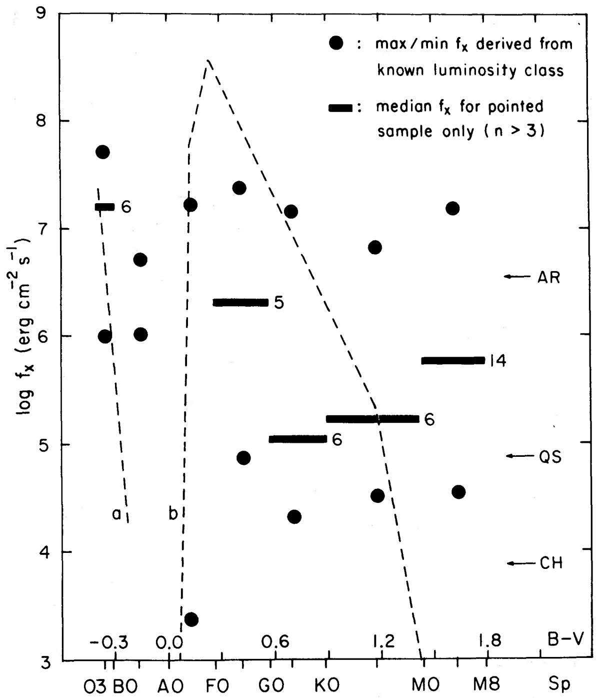

FIG. 5.—Variation of derived X-ray surface flux f_x *vs.* spectral type for main-sequence stars only. Circles indicate the maximum and minimum observed f_x for main-sequence stars in the optically well-classified sample; bars indicate the median f_x for the Pointed sample of main-sequence stars only (calculated only if this sample contained more than three stars; this number is indicated next to each bar).

For comparison we plot the variation in total available acoustic surface flux f_a as a function of spectral type predicted by: (*a*) Hearn (1972, 1973) and (*b*) Renzini *et al.* (1977); more recent calculations by Ulmschneider and collaborators suggest that acoustic flux levels at very late spectral types may have been severely underestimated by Renzini *et al.* (Ulmschneider, private communication), but such revisions do not appear to suffice to eliminate the discrepancies between theory and observations. We note that f_a places a very strict upper bound on f_x if acoustic heating dominates (as such heating must also account for chromospheric, etc., losses, which are not shown here); as discussed in the text, the vastly different qualitative variation of f_a and f_x appears to exclude acoustic heating as a viable universal coronal heating mechanism.

As a guidepost we have also indicated in the right-hand margin the typical values of soft X-ray surface flux for various solar features (AR = active region, QS = Quiet Sun, CH = coronal hole) taken from Vaiana and Rosner (1978); we note that the range of observed stellar surface fluxes corresponds fairly well to that of the inhomogeneous solar corona.

X-ray luminosity function for any fixed spectral type along the main sequence later than spectral type A, suggesting that coronal activity levels are determined by additional parameters (e.g., stellar rotation [Ayres and Linsky 1980*b*; Rosner and Vaiana 1979] and confining magnetic fields [Rosner, Tucker, and Vaiana 1978; Walter *et al.* 1980*a*, *b*]). There is also an observed increase in f_x with $B - V$ for late-type dwarfs, contrary to the expected sharp drop seen in f_a. This decrease of f_a with decreasing stellar mass along the main sequence appears to be an essential (and unavoidable) element of all acoustic heating models; it is a consequence of the strong

[16] For example, Walter *et al.* (1980*a*) review observations of RS CVn stars (principally from *HEAO 1*), which show anomalously high coronal activity levels, given both the relatively high ($\gtrsim 10^7$ K) observed coronal temperatures and relatively low surface gravity of the stars involved. Walter *et al.* point out that the large observed coronal emission measure can only be understood if the X-ray emitting plasma is confined to the stellar surface by forces other than gravity, such as Lorentz forces exerted by surface magnetic fields (see Noci 1973; Pneuman 1973; Rosner, Tucker, and Vaiana 1978). This particular point has been further amplified by spectroscopic studies of Capella using the Solid State Spectrometer of *Einstein* (Holt *et al.* 1979; see also Swank *et al.* 1979 for similar data on the RS CVn star UX Ari) which show that magnetic confinement of coronal plasma seems unavoidable if the high-temperature component of Capella's corona is to be understood. We also note that earlier studies of stellar *chromospheric* activity similarly concluded that standard models invoking acoustic heating were inadequate to account for the observations of late type dwarf Ca II emission (viz., Blanco *et al.* 1974) or the apparent absence of a dependence of Mg II surface flux on stellar gravity (Linsky and Ayres 1978; Basri and Linsky 1979). Furthermore, a direct search by *OSO 8* investigators for the acoustic flux required to heat the upper chromosphere and corona appears to exclude its existence (cf. Athay and White 1979 and references therein).

dependence of the acoustic flux upon the magnitude of the turbulent velocity at the stellar surface, and the decrease of this flow speed with decreasing stellar mass (and bolometric luminosity; see reviews by Jordan 1973 and Kippenhahn 1973).

c) A Possible Alternative: Magnetic Field Dominated Coronae

One possible alternative to canonical acoustic coronal heating models which we have been pursuing is that stellar magnetic fields play the dominant role in determining the level of quiescent coronal emission by (1) channeling free energy to the corona, (2) allowing nongravitational confinement of hot plasma, and (3) actively participating in the coronal heating process (Tucker 1973; Rosner *et al.* 1978; Rosner and Vaiana 1979; Golub *et al.* 1980, 1981; Linsky 1980; Vaiana 1980; Walter *et al.* 1980*a*). In this scenario, the modulation of the surface magnetic flux level (for example, by variations in interior stellar convection and stellar rotation in late-type stars) and the level of stressing of surface magnetic fields (by surface turbulence) together determine the variation of the X-ray luminosity function in the H-R diagram (e.g., variation in both its mean and its spread). Thus coronal activity may be fixed by (i) convection and rotation-driven magnetic dynamo activity and surface convective turbulence together producing magnetically confined coronae in late-type stars; (ii) surface turbulence (driven by rotational, radiative, or pulsational stellar surface instabilities) acting directly on a magnetically confined atmosphere, or on the remnant surface flux of primordial stellar magnetic fields which in turn heats the outer confined atmospheres of early type stars;[17] and (iii) turbulent convection acting on dynamo-generated or primordial magnetic fields in pre–main sequence stars (viz., T Tauri and nebular variables). This conceptual framework is primarily designed to focus and motivate further work, and of course is as yet speculative; it should be seen as a useful departure point for forthcoming observational and theoretical studies of stellar coronae.

It may still be argued that several distinct processes give rise to stellar coronae, and that the standard acoustic heating theories survive only for stars in the spectral range ~ A5–~ G5, with other (perhaps as yet unknown) processes responsible for coronae on other types of stars. This line of reasoning, which attempts to minimize the necessary adjustments, must, however, contend with the results of recent solar coronal research, which have shown that solar coronal X-ray emission is largely modulated by solar surface magnetic fields (see review by Vaiana and Rosner 1978); that is to say, straightforward acoustic heating theory is inadequate to explain observations of the corona of even the G2 V star for which it was originally developed. These difficulties cannot be simply alleviated by, for example, resorting to coupling pure acoustic modes to magnetic modes unless one can demonstrate that the strong dependence of acoustic mode generation upon the magnitude of the turbulent flow velocity can be eliminated; yet the qualitative agreement between acoustically based coronal theories and the data for dwarfs in the spectral range ~ A5–~ G5 suggests that stellar surface turbulence must be a necessary ingredient in any sensible theory.

V. CONCLUSIONS

The *Einstein* stellar survey reported here has established that stars *in general* constitute a new class of low-luminosity galactic X-ray sources. X-ray emission appears to be characteristic of stars from youth (e.g., pre–main sequence) to old age (late type giants and supergiants), crossing virtually all spectral type and luminosity class boundaries, and is in all probability associated with the presence of stellar coronae. The preliminary *Einstein* results thus settle the long controversy surrounding the pervasiveness of the coronal phenomenon in the affirmative, raise a multitude of new questions regarding the formation process responsible for stellar coronae, and clearly contradict standard theories of coronal X-ray emission.

Previous observational studies had shown certain types of stars to be persistent low-luminosity X-ray sources (principally the RS CVn stars, Walter *et al.* 1980*a*), and had suggested that other classes of stars may also be X-ray sources (for example, A stars [Topka *et al.* 1979; Cash, Snow, and Charles 1979; den Boggende *et al.* 1978]); but these data were not sufficient to establish whether the observed X-ray sources are exceptional stars or represented the norm. Optical and, more recently, UV observations of stellar emission characteristic of chromospheres and solar-like transition regions had led to the inference that certain types of stars (principally the "active" late type dwarfs and giants) might well have hot coronae (see Wilson 1966; Blanco *et al.* 1974; Linsky 1977; Hartmann *et al.* 1979; Linsky and Haisch 1979). These relatively indirect results have been both confirmed and vastly extended by the ongoing work described here to stars of all activity levels.

The *Einstein* Stellar Survey will continue to explore the coronal phenomenon, focusing in particular upon (*a*) further investigation of the X-ray luminosity functions for the various stellar categories, shown here in preliminary form, (*b*) establishing stellar X-ray spectral characteristics in the H-R diagram; (*c*) correlating stellar X-ray emission with other stellar characteristics, including age, rotation, surface magnetic fields (viz., Ap stars), and possibly related emission phenomena in the radio, optical, and UV; (*d*) placing limits upon the stellar contribution to the diffuse soft X-ray background and to the integrated emission from stellar clusters and galaxies.

[17] Recently Lucy and White (1980) have suggested an alternative possibility, which involves wind instabilities and consequent shock-heating in the expanding atmosphere of early type stars, and does not invoke magnetic fields. Following their scenario, one would require a transition between early and late type stellar coronae which reflects the relative dominance of plasma heating by local (wind) instabilities and photospherically generated, propagating modes.

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