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AN *EINSTEIN OBSERVATORY* X-RAY SURVEY OF MAIN-SEQUENCE STARS WITH SHALLOW CONVECTION ZONES

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ABSTRACT

We report the results of an X-ray survey of bright late A and early F stars on the main sequence ($m_v < 6.5$, $0.1 \leq B-V \leq 0.5$, luminosity classes IV–V). Only stars without any spectral peculiarities, listed in the *Yale Bright Star Catalogue* and observed by the *Einstein Observatory*, were included in our sample. We find significantly larger X-ray luminosities for the sample binaries than for the single stars; we construct maximum likelihood X-ray luminosity distribution functions for single stars and binaries and argue that the difference in X-ray luminosity is due to the presence of multiple X-ray sources in binaries. We show that the X-ray luminosities for single stars increase rapidly with increasing color, and we demonstrate that the relation $L_x/L_{bol} \approx 10^{-7}$, which holds well for O and B stars, does not hold for A stars . For the full sample, we find no correlation between X-ray luminosity and projected equatorial rotation velocity, but for stars with $B-V > 0.3$, a weak correlation may exist. We argue that the observed X-ray emission in our sample stars originates from coronae, produced by magnetic dynamos in the convection zones of these stars, and discuss the evidence supporting this point of view.

Subject headings: convection — stars: binaries — stars: rotation — X-rays: sources

I. INTRODUCTION

Stellar structure theory predicts the appearance of subphotospheric convection zones for main-sequence stars with masses below $\sim 1.6\ M_\odot$ or effective temperatures below ~ 8000 K (see Gilman 1980). The exact parameter values of the surface gravity g and effective temperature T_{eff}, for which surface convection zones do not exist, depend quite sensitively on the choice of α, the ratio between mixing length and pressure scale height in the computed stellar models, and also somewhat on the opacities used. Clearly, an important task for observational astronomy is to verify or refute this prediction and possibly constrain the allowed values of α.

At optical wavelengths most of the observed flux emanates from the photosphere, which is dominated by radiative transport regardless of whether subphotospheric convection zones exist or not. If, however, these convection zones do exist, they may reach up to layers of optical depth of about unity, where the optical continuum emerges. Hence, earlier studies (Böhm-Vitense 1978, 1981) have compared the observed continuum flux distribution in A and F stars to radiative equilibrium models: Böhm-Vitense (1978) finds strong disagreement between radiative equilibrium models and the observed continuum flux for alls stars with $B-V > 0.22$ and some disagreement for many stars with $0.14 < B-V < 0.22$. A major drawback of her approach is the need for elaborate model calculations, and the correct interpretation of small deviations between predictions and observations. In addition, the ultraviolet continuum flux tends to depend sensitively on the assumed metal abundances and opacities; the convective models used by Böhm-Vitense (1978) are empirical models obtained from extrapolation of solar models; and, finally, it is not clear how rapid rotation, encountered in A and early F stars, precisely influences the continuum flux distribution. Hence it seems desirable to look for more model-independent indicators of convection in stars.

Using the solar analogy, we may expect stars with subphotospheric convection zones to exhibit phenomena similar to those observed on the Sun, i.e., magnetic fields (presumably produced by some dynamo process), which in turn are essential in the formation of chromospheres, transition regions, and coronae. Detection of hot matter in the envelopes of these stars may therefore serve as indirect evidence for the existence of subphotospheric convection zones. The *International Ultraviolet Explorer* (*IUE*) has been used to search for chromospheric and transition-line emission from A and F stars (Linsky and Marstad 1980; Böhm-Vitense and Dettmann 1980; Saxner 1981; Brown and Jordan 1981; Blanco, Catalano, and Marilli 1980; Crivellari and Praderie 1982). Stars with spectral type later than about F0–F2 are often found to show chromospheric emission lines (Linsky 1982, Böhm-Vitense and Dettmann 1981); stars of earlier type are not. Crivallari and Praderie (1982) have not found any emission lines in a sample of nine A stars with spectral type A5–A7 and luminosity classes III and V; Blanco, Catalano, and Marilli (1980), on the other hand, claim the detection of chromospheric Mg II emission in Altair (A7 V, $B-V = 0.22$).

In the optical waveband, a search for chromospheric emission lines in the cores of the Ca II H and K by Dravins (1980) in a sample of eight young main-sequence A stars has also been negative (see also his discussion of various claims for detection of chromospheres in A stars). However, absence of evidence is no evidence for absence; as pointed out by Dravins (1980), Linsky (1982), and Walter *et al.* (1984), the failure to detect any emission may be simply due to the enhanced photospheric continuum and rotational line broadening in these hotter and more rapidly (as compared to G or K stars) rotating stars rather than to a complete absence of transition regions and coronae.

At X-ray wavelengths, both photospheric background and

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rotational line broadening effects are unimportant. A detection in X-rays provides the most direct evidence for the existence of hot plasma (typically at temperatures in excess of 10^6 K) in the envelopes of these stars, and for the action of some heating process. By using the solar analogy, we also infer the existence of convection zones and magnetic fields. Alternatively, the X-ray emission may be produced in a stellar wind.

Previous studies of the X-ray emission from F type stars have been undertaken by Topka *et al.* (1982) and Walter (1983). Topka *et al.* (1982) studied a magnitude-limited sample ($m_V <$ 8.5) of serendipitously detected F stars (18 detections, 37 upper limits); they conclude that the average emission for main-sequence F stars is of the order of 10^{29} ergs s^{-1}. Further, they claim that the level of emission does not vary with spectral type as well as that the mean X-ray luminosity of the early F stars is even higher than 10^{29} ergs s^{-1}; this should be contrasted with the fact that they detected only four out of 43 sampled A stars. However, most of the Topka *et al.* (1982) sample consists of fainter (i.e., $8.5 > m_V > 6.5$) stars, whose spectral classification is somewhat uncertain, and for which very little additional information about rotation and/or multiplicity is available; in fact, for most stars in the sample used by Tokpka *et al.* (1982), only the distance-independent ratio of X-ray and optical luminosity $L_x/L_{\rm opt}$ could be directly observed.

Walter (1983) presents a sample of 14 pointed observations of bright (i.e., $m_V < 6.5$) F dwarfs; all but one star (HR 17) were detected, however, at levels somewhat lower than reported for the Topka *et al.* (1982) sample. In addition, many of the stars in Walter's (1983) sample are binaries; it is therefore not clear *a priori* which component is the dominant X-ray emitter and what conclusions about coronae in F stars (rather than late-type dwarfs) can be drawn, and we have in fact reached conclusions exactly the opposite to Walter (1983).

This study presents a comprehensive investigation of the X-ray properties of late A and F stars. It utilizes almost all of the available X-ray data on bright A and F stars observed by the *Einstein Observatory*, and the data have all been (re-)analyzed in a uniform fashion. The main focus of this paper is whether and what X-ray observations of stars tell about the onset of convection; thus, it contains the presentation of the data and their interpretation. In a second paper (Schmitt 1984) we will give a detailed discussion of the statistical techniques used for the analysis, some of which were especially developed for surveys of the kind at hand.

The detailed outline of the paper is as follows: in § II we review the survey composition, compare it in detail to earlier studies, and present our data. In § III we investigate the effects of multiplicity on the level of X-ray emission and construct X-ray luminosity distribution functions for various subsamples. We discuss the nature of the X-ray emission from binary as well as single stars and study correlations between X-ray luminosities and rotation. Section IV contains our discussion and conclusions; in particular we review X-ray observations of early A stars and present a uniform picture encompassing all the available observations. Appendix A contains some details concerning the detection algorithm used and the source recognition procedures adopted; Appendix B gives a thorough discussion of the UV transmission properties of the HRI on board the *Einstein Observatory* and its consequences for the interpretation of the X-ray emission from A type stars.

II. OBSERVATIONS AND ANALYSIS

Most of the X-ray data used for this study have been obtained with the Imaging Proportional Counter (IPC) onboard the *Einstein Observatory* (see Giacconi *et al.* 1979 for a full description of the instrument). Five stars were observed with the High Resolution Imager (HRI) only, and for two nearby stars in our sample, Altair and Procyon, both IPC and HRI pointings are available. The adopted survey procedures differ considerably from procedures used in previous surveys (cf. Topka *et al.* 1982); new software, developed for REV1 IPC processing, was utilized, and we discuss some of the advantages of our approach in more detail in Appendix A.

a) Survey Composition

Our survey comprised all stars satisfying the following criteria: (*a*) the star must be listed in the *Bright Star Catalogue* (Hoffleit 1982); (*b*) the star must have $B-V$ color in the range $0.1 \leq B-V \leq 0.5$; and (*c*) the star must have been observed by the *Einstein Observatory* for at least 500 seconds. The *Bright Star Catalogue* (Hoffleit 1982) is almost complete to 6.5 mag, and contains a few stars between magnitudes 6.5 and 7.0. We chose the *Bright Star Catalogue* (rather than, for example, the SAO catalog) for our survey, since considerably more information such as photoelectric magnitudes and colors, radial velocities, reliable spectral classification, information on multiplicity, is available for most of its entries. Yet, for ~500 bright stars there is still no photoelectric photometry available, 10 of which happened to fall within our survey fields.

Color provides a more reliable indicator of effective temperature than spectral type; in terms of spectral type, the range $0.1 \leq B-V \leq 0.5$ spans ~A5 to ~F7. We considered both dwarfs and subgiants but rejected all giants and supergiants. Furthermore, we rejected all stars with peculiar spectra and/or metal overabundances, spectrum variables, RS CVn objects, and so on; in the case of binaries, we rejected all stars whose optical light is not dominated by the A or F star, for example, a dwarf and late-type giant.

Most guest observers, as well as the Columbia and MIT consortium members, kindly gave us permission to use these fields into which survey stars fell. Due to F. Walter's courtesy, we could in particular include and reanalyze all the stars in his sample (Walter 1983), except one whose color puts it beyond our color cutoff at $B-V = 0.5$. Hence only ~10 fields could not be analyzed. The total survey, as reported here, consists of 125 stars. Our survey comprises both pointed and serendipitous pointings; pointed observations are usually available for the brighter, nearby stars, whereas many of the fainter, more distant stars have only been observed serendipitously.

The threshold for source acceptance (cf. Appendix A) was chosen in such a way that the probability of mistakenly identifying a purely statistical background fluctuation in an otherwise empty field as a source was set at 10^{-2}. Hence the probability of making at least one spurious identification becomes 0.5 for about 70 pointings at actually source-free positions, and thus we expect to have about one spurious detection in our sample. Had we chosen the cutoff at a probability of 10^{-3}, we would expect essentially no spurious sources, and our sample would contain eight fewer detected sources. We wish to emphasize that the quoted numbers merely refer to the probability of interpreting statistical background fluctuations as sources but not to misidentifications of real X-ray sources. The probability, however, that a "background" galactic or extragalactic X-ray source falls right on the position of a bright star in the range $0.1 \leq B-V \leq 0.5$ is quite small.

Furthermore, we wish to point out that the composition of our survey may be biased. We found it impractical to consider only genuine serendipitous sources; these sources tend to be far off center, where the image quality and effective exposure times are considerably reduced. Furthermore, many of the bright and nearby stars were observed in the pointed survey; if we did not use these data, we would lose most of our highest quality and largest sensitivity data; many of the nearby stars sample the low luminosity tails of the X-ray distribution functions we construct, and not using these data would thus introduce yet another bias. In short, we think that it is not possible to construct a truly unbiased sample; however, we did check the validity of our conclusions by considering subsamples.

It is constructive to compare the present sample to the samples used for earlier studies of X-ray emission in F stars. Only three stars in Topka *et al.* (1982) are also in our sample, HR 1436 (which is partially obscured by the IPC window support ribs), HR 1935, and HR 4574, which is actually classified as A9 V in Hoffleit (1982); only one of those three stars is within 30 pc (HR 1935). We therefore conclude that the two samples are essentially disjoint; hence, it should not be surprising to find differences between the two. Walter's (1983) sample per se (14 stars) is too small and too heterogeneous to allow any meaningful statistical conclusions.

b) The Data

In Figure 1 we plot the logarithm of the observed X-ray luminosity in the 0.15–4.0 keV band versus $B-V$ color for all sample stars; we distinguish between single stars, or rather, stars not known to be binaries (squares denote unobscured single stars; triangles, single stars near rib or edge), and stars which cannot be resolved by the IPC, i.e., spectroscopic or close visual binaries (pluses denote unobscured, stars; crosses, partially obscured stars); we also show all the obtained upper limits, for which the distinction between single stars and binaries is unnecessary (at the moment). In order to obtain L_x, we followed the procedures described in Appendix A; we chose trigonometric parallaxes, with an eye toward compatability of trigonometric and spectroscopic parallaxes, and spectroscopic parallaxes for the more distant stars without trigonometric parallex measurements. This procedure may lead to significant errors in L_x, particularly for the stars with $B-V > \sim 0.25$, whose luminosity class is in question; note in this context that our sample contains no giants, only subgiants and dwarfs. We also plot the logarithm of the distance independent quantity $L_x/L_{\rm bol}$ for all our survey stars versus the color $B-V$ in Figure 2; in order to compute the bolometric flux, we assigned effective temperatures on the basis of color following Böhm-Vitense (1981) and computed bolometric corrections as in Allen (1973). All the data displayed in Figures 1 and 2 are presented in tabular form in Table 1, where we list the HR numbers of all the survey stars, their V magnitudes and $B-V$ colors, the logarithms of L_x and $L_x/L_{\rm bol}$, the distance assumed to compute L_x, and an indication of whether we treated the star as single (S) or binary (B) as far as its X-ray emission is concerned; we have also marked those stars with a footnote which would have been considered as nondetections had we used a more stringent cutoff probability of 10^{-3} (see above).

Both Figures 1 and 2 show essentially the same trends; for $B-V > \sim 0.26$–0.30, we find many detections ranging from log $L_x \sim 27.5$ to ~ 29.5; only a few upper limits are found at levels comparable to the lowest detections. On the other hand, for $B-V < \sim 0.26$–0.30 we find a few detections, but mostly upper limits only. Most of the detections in this $B-V$ range are actually binaries, for which the observed X-ray emission may be due to a low mass companion (Golub *et al.* 1983); note that the data point at $B-V = 0.22$, log $L_x = 27.14$ is Altair (~ 300 counts in 11,000 s), a nearby single star (A7 V), which has already been reported by Golub *et al.* (1983).

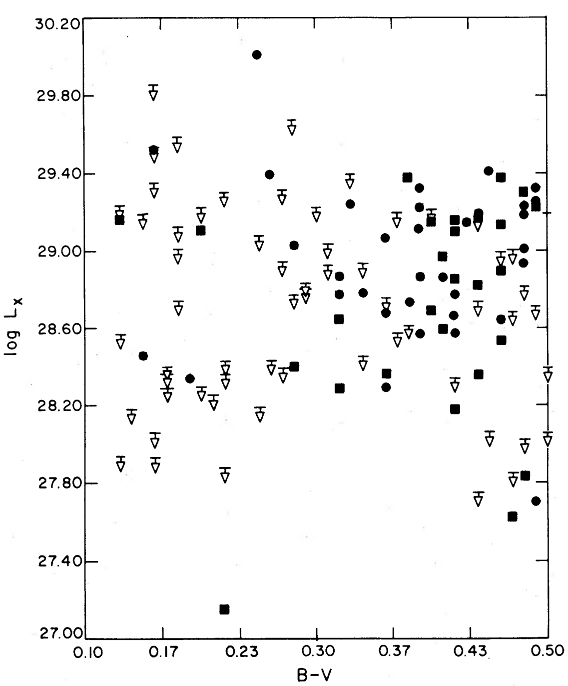

FIG. 1.—X-ray luminosity–color ($B-V$) diagram of detections and upper limits for all stars in our survey. Presumably single stars are indicated by squares, and spectroscopic or close visual binaries are indicated by circles. Upper limits are indicated by downward arrows, regardless of multiplicity.

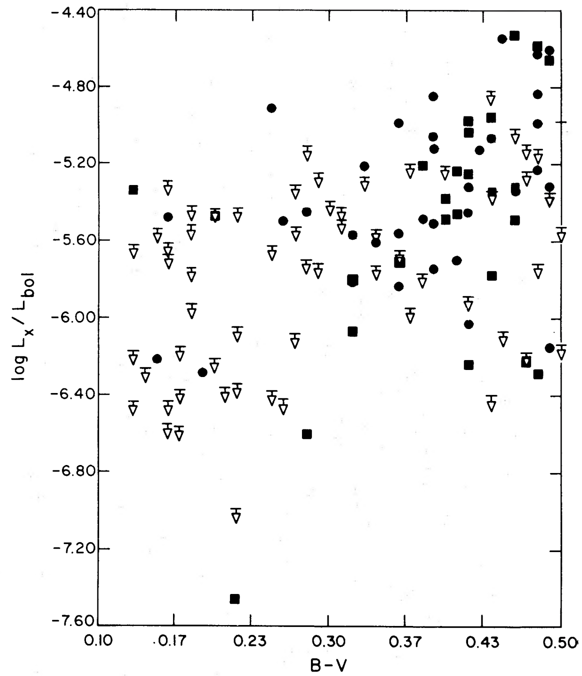

FIG. 2.—Ratio of X-ray luminosity to bolometric luminosity vs. color ($B-V$) diagram for all stars in our survey. Symbols are as in Fig. 1.

TABLE 1

CHARACTERISTICS OF THE SURVEY STARS

HR	V	$B-V$	Log L_x	log L_x/L_{bol}	d (pc)	S/B
17	6.19	0.48	<28.02	< −5.72	23.0	S
32	6.64	0.37	<29.19	< −5.20	60.0	B
327[a]	6.25	0.40	29.16	−5.38	59.0	S
368[a]	5.70	0.42	<28.34	< −5.89	32.0	S
410[a]	6.31	0.47	<28.68	< −5.24	30.0	S
492[a]	5.75	0.44	<29.17	< −4.82	25.0	B
544	3.41	0.49	29.32	−5.32	18.0	B
553[a]	2.64	0.13	<28.57	< −6.17	13.5	B
591	2.86	0.28	28.40	−6.60	21.0	S
657[a]	5.58	0.49	<28.71	< −5.35	25.0	B
778	5.31	0.27	<28.39	< −6.08	35.0	S
818	4.47	0.48	29.01	−4.99	14.0	B
878	5.80	0.41	28.97	−5.24	33.0	S
919	4.09	0.16	<27.93	< −6.43	17.0	S
988[a]	6.14	0.40	<29.21	< −5.21	49.0	S
1014[a]	6.05	0.13	29.17	−5.34	50.0	S
1233	6.37	0.42	29.15	−4.98	39.0	S
1309	5.29	0.36	28.68	−5.56	27.0	B
1331[a]	5.65	0.28	29.02[b]	−5.45[b]	41.0	B
1351[a]	5.59	0.28	<28.77	< −5.70	40.0	B
1356	5.26	0.22	<28.43	< −6.05	34.0	B
1358[a]	6.17	0.46	28.64[b]	−5.34[b]	30.0	B
1380[a]	4.80	0.15	28.46[b]	−6.21[b]	34.0	B
1391	6.46	0.49	29.25	−4.61	30.0	B
1394	4.49	0.25	30.01	−4.91	40.0	B
1408	5.90	0.32	28.64[b]	−5.81[b]	45.0	S
1422[a]	5.58	0.32	28.86	−5.57	38.0	B
1427	4.78	0.17	<28.36	< −6.56	45.0	B
1432[a]	6.02	0.34	<28.45	< −5.73	35.0	B
1436[a]	6.39	0.42	28.85	−5.25	38.0	S
1444	4.65	0.25	<28.19	< −6.38	29.0	B
1466[a]	5.35	0.32	28.77[b]	−5.80[b]	40.0	B
1613	6.32	0.28	<29.67	< −5.11	80.0	S
1686	5.05	0.47	<27.85	< −6.18	19.0	S
1859	6.03	0.34	<28.93	< −5.55	50.0	B
1882[a]	6.19	0.22	<29.30	< −5.43	70.0	B
1935	5.31	0.46	28.53	−5.49	21.0	S
1937	4.80	0.13	<27.94	< −6.43	24.0	B
1959	6.42	0.30	<29.22	< −5.40	70.0	B
1983	3.60	0.47	27.62	−6.22	7.8	S
2015	4.35	0.21	<28.25	< −6.36	26.0	S
2124	4.12	0.16	29.52	−5.48	36.0	B
2740	4.49	0.32	28.28	−6.07	21.0	S
2846	5.22	0.39	29.32	−4.85	24.0	B
2943	0.38	0.42	28.17	−6.24	3.4	S
3310[a]	6.32	0.18	<29.58	< −5.42	100.0	B
3499[a]	6.25	0.49	29.23	−4.66	28.0	S
3569	3.14	0.19	28.34	−6.28	15.0	B
3798	6.46	0.33	29.24	−5.21	58.0	B
3893	6.24	0.48	29.18	−4.84	32.0	B
3991	5.31	0.36	28.29	−5.84	24.0	B
3998[a]	6.44	0.46	<28.99	< −5.02	35.0	B
4054[a]	4.79	0.45	<28.06	< −6.07	19.0	S
4060[a]	6.32	0.33	<29.39	< −5.27	70.0	S
4302	6.23	0.31	<28.92	< −5.49	50.0	B
4366[a]	6.67	0.27	<28.94	< −5.53	65.0	B
4413	5.17	0.50	<28.06	< −6.16	25.0	B
4574	6.42	0.29	<28.80	< −5.25	36.0	B
4688[a]	6.33	0.50	<28.39	< −5.53	30.0	S
4825	3.65	0.36	29.06	−4.99	10.1	B
4826	3.65	0.36	29.06	−4.99	10.1	B
4867	5.85	0.46	29.37	−4.54	24.0	S
4875	5.89	0.15	<29.19	< −5.54	60.0	S
4914	5.60	0.34	28.78	−5.61	37.0	B
4916	5.24	0.28	<28.39	< −6.00	31.0	S
4934	6.00	0.41	28.59	−5.46	30.0	S
4968	5.22	0.45	29.41	−4.55	19.0	B
5000[a]	6.07	0.44	29.17[b]	−4.96[b]	34.0	S
5050	5.75	0.42	28.77	−5.32	28.0	B
5062	4.01	0.16	<28.06	< −6.55	22.0	B
5128[a]	5.83	0.40	28.69	−5.49	32.0	S
5177	6.50	0.47	<29.00	< −5.10	40.0	S
5185	4.50	0.48	28.93	−5.23	17.0	B
5328[a]	6.69	0.39	28.86[b]	−5.51[b]	60.0	B
5365	5.41	0.38	29.37	−5.21	42.0	S
5404	4.05	0.50	29.19	−4.98	14.0	B
5418[a]	5.94	0.16	<29.35	< −5.61	80.0	S
5447	4.46	0.36	28.36	−5.71	15.0	S
5482[a]	5.36	0.29	<28.83	< −5.72	39.0	B
5529	6.16	0.36	<28.75	< −5.65	48.0	S
5610	6.50	0.31	<29.03	< −5.43	60.0	B
5679[a]	5.63	0.18	<28.74	< −5.93	50.0	S
5747	3.68	0.28	<28.44	< −6.57	31.0	B
5774	5.02	0.07	<29.07	< −5.96	55.0	B
5788	3.80	0.26	<28.43	< −6.42	27.0	B
5789	3.80	0.26	<28.43	< −6.42	27.0	B
5919	6.29	0.18	<29.12	< −5.52	65.0	S
5933	3.85	0.48	27.83	−6.29	12.0	S
6012	6.47	0.44	28.36[b]	−5.78[b]	41.0	S
6052[a]	6.50	0.39	29.22	−5.06	49.0	B
6327[a]	5.91	0.38	<28.61	< −5.77	42.0	B
6361	6.38	0.20	<29.22	< −5.44	70.0	B
6370	5.80	0.48	29.33	−4.63	22.0	B
6493	4.54	0.39	28.57	−5.75	21.0	B
6561	3.54	0.26	29.39	−5.50	25.0	B
6562	5.94	0.37	<28.57	< −5.95	50.0	S
6596[a]	4.80	0.43	29.14	−5.13	22.0	B
6670	5.77	0.42	28.57	−5.45	26.0	B
6798[a]	6.36	0.16	<29.85	< −5.29	120.0	B
6927	3.57	0.49	27.70	−6.15	7.8	B
7034[a]	6.31	0.48	<28.81	< −5.12	30.0	S
7061	4.19	0.46	28.89	−5.49	19.0	S
7141	4.62	0.17	<28.29	< −6.37	31.0	B
7142	4.98	0.20	<28.30	< −6.21	31.0	B
7152	4.87	0.41	28.86	−5.70	32.0	B
7160	6.30	0.20	29.10	−5.46	60.0	S
7214[a]	5.83	0.18	<29.01	< −5.74	60.0	B
7267	6.48	0.52	28.83	−5.31	41.0	B
7340	3.93	0.22	<28.26	< −6.34	24.0	B
7354[a]	6.35	0.44	<28.73	< −5.34	36.0	S
7469	4.48	0.38	28.73	−5.49	18.0	B
7550[a]	6.53	0.44	29.18	−5.07	48.0	B
7557	0.77	0.22	27.14	−7.46	5.0	S
7588[a]	6.39	0.16	<29.53	< −5.67	130.0	B
7736	4.97	0.14	<28.18	< −6.26	28.0	B
7925	6.01	0.46	29.13	−5.32	48.0	S
8162	2.44	0.22	<27.88	< −6.99	14.7	S
8400	5.03	0.44	28.82	−5.35	22.0	S
8430	3.76	0.44	<27.75	< −6.40	12.0	B
8441[a]	6.11	0.27	<29.31	< −5.31	60.0	B
8740[a]	5.51	0.25	<29.07	< −5.63	50.0	S
8868	5.55	0.39	29.11	−5.12	30.0	B
8880	4.60	0.17	<28.40	< −6.15	27.0	S
8971[a]	5.95	0.13	<29.23	< −5.62	70.0	B
9072	4.01	0.42	28.66	−6.03	25.0	B

[a] Star partially obscured by IPC rib or edge.

[b] "Detection" would become "upper limit" if threshold were raised from 10^{-2} probability to 10^{-3}.

III. RESULTS

a) *Effects of Multiplicity*

The interpretation of the X-ray data with regard to the existence of hot coronae is complicated by multiplicity effects. Late-type dwarfs of spectral type G, K, or M may have X-ray luminosities of up to 10^{29} ergs s^{-1} and more (Vaiana *et al.* 1981; Rosner *et al.* 1981), and thus the optically bright star in a multiple system need not be the X-ray bright star. In addition, in a binary system consisting of a late-type dwarf together with an early type, i.e., A or F dwarf, the optically faint companion is expected to be young, and hence correspondingly more active (Golub *et al.* 1983). We can show the presence of the effect discussed above in our data in three ways.

First, we present *direct evidence* in the case of the common proper motion pair HR 1982, a K2 V dwarf ($V = 6.15$, $B-V = 0.94$), and HR 1983 (γ Lep), a F dwarf ($V = 3.6$, $B-V = 0.47$) at a separation of 96″. This separation would make the two stars almost certainly indistinguishable in the IPC, particularly if both components have soft X-ray spectra with temperatures $\log T \approx 6.3$. We have, however, obtained an HRI pointing, which clearly separates the two X-ray sources and shows that the count rate from the K dwarf exceeds the count rate from the F dwarf by a factor 6.6; therefore the ratio of X-ray to optical flux is ~ 70 times larger for the K dwarf as compared to the F dwarf.

Second, we will demonstrate that the (cumulative) *X-ray luminosity distribution function* $B(L_x)$ for the known binaries is significantly different from the (cumulative) *X-ray luminosity distribution function* $S(L_x)$ for the single stars. We restrict our sample to stars in the range $0.30 \leq B-V \leq 0.50$ within 30 pc, i.e., to a volume-limited sample; for these stars trigonometric parallaxes are generally available, and we avoid introducing unnecessary uncertainties into the inferred X-ray luminosities by using spectroscopic parallaxes. The sample consists of 11 detections and six upper limits for single stars, and of 21 detections and four upper limits for binaries. We construct the maximum likelihood (ML; Kaplan and Meier 1958; Avni *et al.* 1980; Schmitt 1984) estimate of the cumulative distribution function for the single stars and binaries (see Fig. 3). There exists a variety of statistical techniques to test the null hypothesis

$$H_0\colon \quad B(L_x) = S(L_x) \quad \text{for} \quad 0.3 \leq B-V \leq 0.5\ ,$$

i.e., the two samples are drawn from the same parent population, against the alternative hypothesis H_1

$$H_1\colon \quad B(L_x) > S(L_x) \quad \text{for at least one value in} \quad 0.3 \leq B-V \leq 0.5\ ,$$

i.e., the two samples are drawn from intrinsically different parent populations, in the presence of upper limits in one or both samples; these techniques are discussed in more detail by Schmitt (1984). All the applied tests reject the null hypothesis H_0 at more than the 98% confidence levels. Hence we conclude that the distribution functions for single stars and binaries differ significantly. We especially emphasize that the above conclusion does *not* depend on the choice of our subsample: the same analysis was carried out for the full data set and for other subsamples, in all cases the null hypothesis H_0 was rejected at similar confidence levels.

Third, we show that two important characteristics of the single star distribution function $S(L_x)$ and the binary distribution function $B(L_x)$, *the mean and the median*, are significantly different for both distributions by simply calculating mean and median with the appropriate error bars; this should of course not come as too big a surprise since we have already demonstrated that the two distribution functions are significantly different.

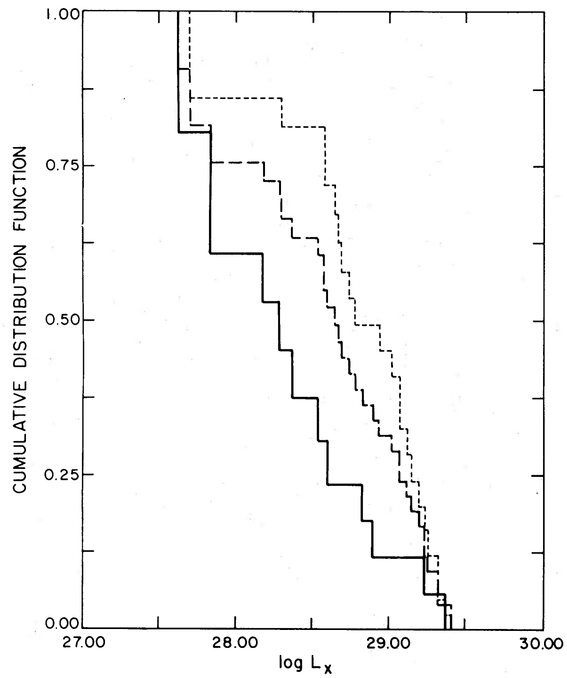

FIG. 3.—Cumulative distribution functions for the single stars (*solid line*), binaries (*short-dashed line*), and the total sample (*long-dashed line*) of stars within 30 pc and in the color range $0.3 \leq B-V \leq 0.5$.

Within a distance of 30 pc, 11 detections and six upper limits were obtained for single stars in our sample stars in the range $0.30 \leq B-V \leq 0.50$. From this subsample consisting of 17 stars, 500 random samples were drawn with replacement ("bootstrapped"; see Efron 1980; Schmitt 1984), and for each sample drawn in this fashion, $(\log L_x)_{\text{mean}}$ and $(\log L_x)_{\text{median}}$ were computed; the results are plotted in Figure 4 (i.e., the two curves centered on $\log L_x = 28.3$) as cumulative distribution functions, i.e., we plot the fractional number of samples resulting in mean and median greater or equal to L_x as a function of L_x. In the same fashion mean and median of the subsample of binaries within 30 pc in the range $0.30 \leq B-V \leq 0.50$ (consisting of 21 detections and four upper limits) were bootstrapped, and the results are also displayed in Figure 4 (the curves centered on $\log L_x = 28.8$). We note in passing that the mean and median of the bootstrapped samples agree well with the mean and median calculated from the original distribution function. Now, in order to obtain, say 1 σ confidence interval for mean and median, we simply determine those values of $\log L_x$, i.e., the independent variable, between which the cumulative distribution function rises from 0.16 to 0.84. The 1 σ confidence intervals for the mean (at $\log L_x = 28.29$) and median (at $\log L_x = 28.28$) of the single star X-ray distribution function are then found to be [28.16, 28.43] and [27.83, 28.36], respectively. In the same way, we find 1 σ confidence intervals of [28.65, 28.88] and [28.68, 29.06] for the mean (at $\log L_x = 28.76$) and the median (at $\log L_x = 28.77$), respectively, of the binary X-ray distribution function.

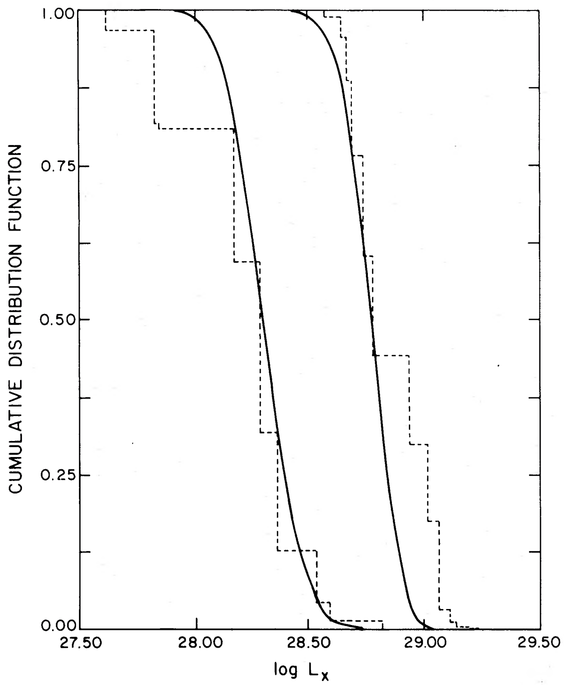

FIG. 4.—Cumulative distribution functions of the bootstrap distributions (see text) for median and mean for single stars (*left pair of curves*) and binaries (*right pair of curves*) in the color range $0.3 \leq B-V \leq 0.5$.

We now note that the errors of the mean of the binary X-ray distribution function (21 detections, four upper limits) are smaller than the corresponding errors of the mean of the single star X-ray distribution function (11 detections, six upper limits), which is to be expected from the sample sizes. Second, we note that the errors for the median are much larger than the errors for the mean; this is of course easily recognized as a discreteness effect in finite (and in fact small) sample statistics.

We argue that the means and medians of the single star and binary X-ray distribution functions are significantly different. The bootstrap distributions for mean and median have only little overlap, and we estimate that only the 2 σ confidence intervals start to overlap. At the same time we have determined the mean and median of the two distributions with their appropriate confidence intervals.

b) *The Onset of "Activity" in Late-Type Stars*

Figures 1 and 2 indicate that the mean levels of X-ray emission for stars in the left-hand side of the diagrams, i.e., for $B-V < 0.3$, seem to be lower than for the stars on the right-hand side of the diagrams, i.e., for $B-V > 0.3$; in addition, considerably fewer significant upper limits have been obtained in this parameter regime. In the following, we will quantify this observation, and in particular argue, that the stars in the ranges $0.1 \leq B-V < 0.3$ and $0.3 \leq B-V \leq 0.5$ have statistically significantly different properties, and that this difference can hence be interpreted as onset of "activity" in late-type stars.

It should be clear from our preceding discussion that only single stars can be meaningfully used for the present purposes; we will consider the binaries separately in § III*c*. The question now arises whether log L_x or log ($L_x/L_{\rm bol}$) should be used as a measure for the X-ray emission of the sample stars. Log $L_x/L_{\rm bol}$ is distance independent and provides a convenient measure of the coronal energy losses scaled by the total, i.e., essentially photospheric energy losses, of a star. On the other hand, despite the small color range covered by our sample, the bolometric luminosities still drop by more than a factor of 12 when going from spectral type A5 to spectral type F5, and hence log $L_x/L_{\rm bol}$ would be expected to increase by the same amount, even if there were no change in log L_x at all across the sample. Since the surface areas of the stars in our sample change by a factor of 4 at the most, log L_x appears to be a better indicator of the efficiency of any presumed underlying magnetic dynamo; however, the L_x values may be corrupted by uncertain distances, particularly for stars beyond 30 pc.

We carried the analysis out in both log L_x and log ($L_x/L_{\rm bol}$) with identical conclusions; hence, we will present here only the results in log L_x, where the confidence intervals are smaller for the reason mentioned above. In the color range $0.1 \leq B-V < 0.3$, there are four detections, two of which we actually suspect of being binary,[2] and 35 upper limits; in the color range $0.3 \leq B-V \leq 0.5$, there are 22 detections and 25 upper limits, and we will also consider the color range $0.3 \leq B-V \leq 0.42$ with 12 detections and 12 upper limits, to explicitly show that our conclusions are independent of the chosen subsamples; note that for all three samples we included the upper limits for binary systems in the upper limits for the single stars.

We constructed ML cumulative X-ray luminosity distribution functions for the stars in the above $B-V$ ranges (see Fig. 5) as before. The X-ray luminosity distribution function for stars with $0.1 \leq B-V < 0.3$ (*solid line* in Fig. 5) lies far below the X-ray luminosity distribution functions for the stars in the other groups (long dashes in Fig. 5 show color range $0.3 \leq B-V \leq 0.5$, short dashes $0.3 \leq B-V \leq 0.42$), and it clearly matters only little how the data in the range $B-V \geq 0.3$ are grouped. If we—as in the preceding section—test the hypothesis that the distribution function for the stars with $B-V < 0.3$ lies above or is equal to the distribution function for the stars with $0.3 \leq B-V \leq 0.5$ or $0.3 \leq B-V \leq 0.42$ with the techniques discussed by Schmitt (1984), we find that we can reject this hypothesis at a confidence level of about 95%, and if the two suspected binaries are excluded from the analysis, at a confidence level of far more than 99%. Hence *the rise in observed X-ray luminosity across our sample is real* and not an artifact of the selected sample.

c) *The Nature of the X-Ray Emission from Binaries*

We have been very careful to distinguish between single stars and binaries in our sample. Having established the fact that single main-sequence F stars with $B-V \geq 0.3$ are X-ray emitters with a mean of about 2×10^{28} ergs s^{-1}, and having constructed their ML distribution function, we can return to the binaries within the same color range, and investigate why their X-ray emission is different as we showed in § III*a*. We will in

[2] The two cases in question are HR 1014 ($m_V = 6.05$, spectral type A3 V; Hoffleit 1982), seen serendipitously almost right on the rib, the centroid of the X-ray emission being about 1′ from the optical position, and HR 7160 ($m_v = 6.32$, spectral type A8 V; Hoffleit 1982), for which only photographic photometry (taken from Hirshfeld and Sinnott 1982) is available. If for both HR 1014 and HR 7160 the X-ray emission were due to, say an M0 dwarf, a value of log ($L_x/L_{\rm bol}$) of about -3 would result, which is still acceptable for highly active M dwarfs; if the companions were G dwarfs, similar to the presumed companion of the F0 dwarf 71 Tau (Peterson *et al.* 1982) with log $L_x = 30.0$, only a modest $L_x/L_{\rm bol}$ ratio would result. We will nevertheless treat both HR 1014 and HR 7160 as "single" stars and show that our conclusions about the onset of convection can be drawn despite "contamination" of our sample with binaries.

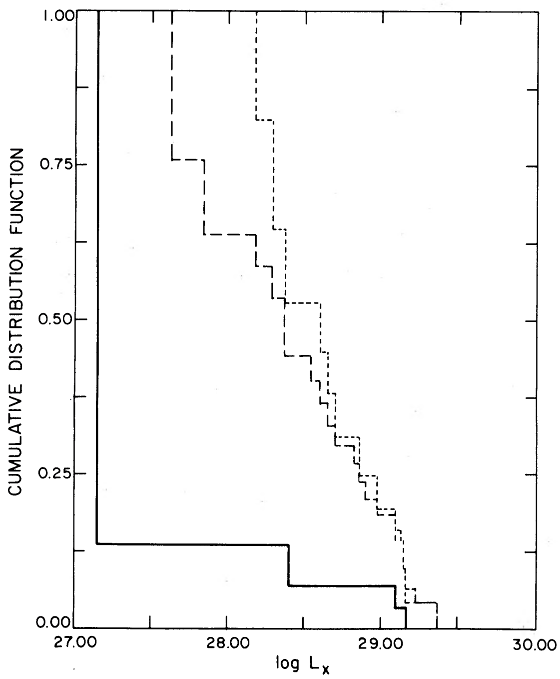

FIG. 5.

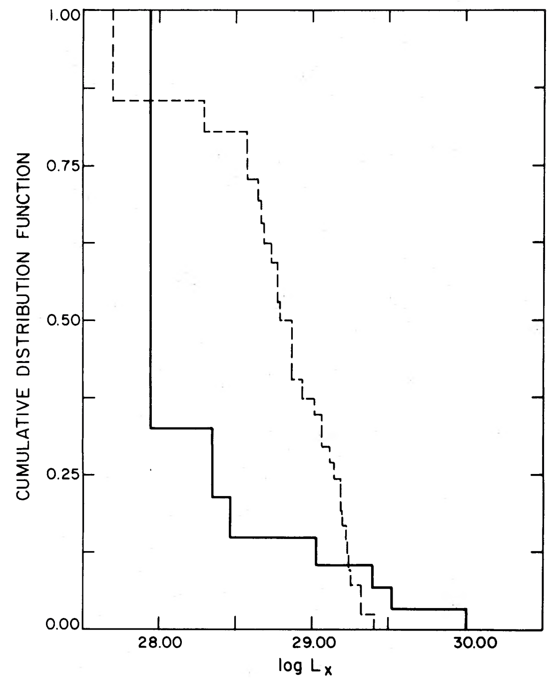

FIG. 6.

FIG. 5.—Cumulative distribution functions for single stars in the color ranges $0.1 \leq B-V \leq 0.3$ (*solid histogram*), $0.3 \leq B-V \leq 0.5$ (*long-dashed histogram*), and $0.3 \leq B-V \leq 0.42$ (*short-dashed histogram*). Calculations included the upper bounds for binaries (see text).

FIG. 6.—Cumulative distribution functions for binaries in the color ranges $0.1 \leq B-V \leq 0.3$(*solid histogram*) and $0.3 \leq B-V \leq 0.5$(*long-dashed histogram*).

fact demonstrate that it is likely that most of the observed binaries are not only multiple optical, but also multiple X-ray sources (cf. the case of HR 1982/83).

First, we find that the binaries in the ranges $0.1 \leq B-V < 0.3$ (six detections, 25 upper limits) and $0.3 \leq B-V \leq 0.5$ (30 detections, 12 upper limits) are statistically significantly different. The ML estimates of the X-ray luminosity distribution functions of the two samples are plotted in Figure 6 (solid line denotes stars with $0.1 \leq B-V < 0.3$, dashed line $0.3 \leq B-V \leq 0.5$). Schmitt (1984) shows in detail that the null hypothesis, i.e., the two samples are drawn from the same parent distribution, can be rejected at a confidence level of far more than 99%. This result is not surprising since we do not expect binary F stars to have convection zones or coronae different from single F stars, whereas an A star in a (wide) binary system is expected to show only weak X-ray emission (see § III*a*).

We will now show that it is not necessary to assume that F stars in binary systems emit at an enhanced level. Using the single F star X-ray luminosity distribution function derived in § III*a* and the M star X-ray luminosity distribution function as derived by Rosner *et al.* (1981), we can calculate the probability convolution of these distribution functions. The observed binary F star distribution function (*dashed line* in Fig. 7) follows the probability convolved distribution function (*solid line* in Fig. 7) very closely.

Hence, the presently available data on F type binaries can simply be explained by assuming that we actually observe a statistically independent mixture of F stars and late-type dwarfs, and no assumption of an intrinsically increased level of X-ray emission in binaries has to be made. We emphasize that we do not claim the uniqueness of this hypothesis but merely its consistency with the available data; also note that we

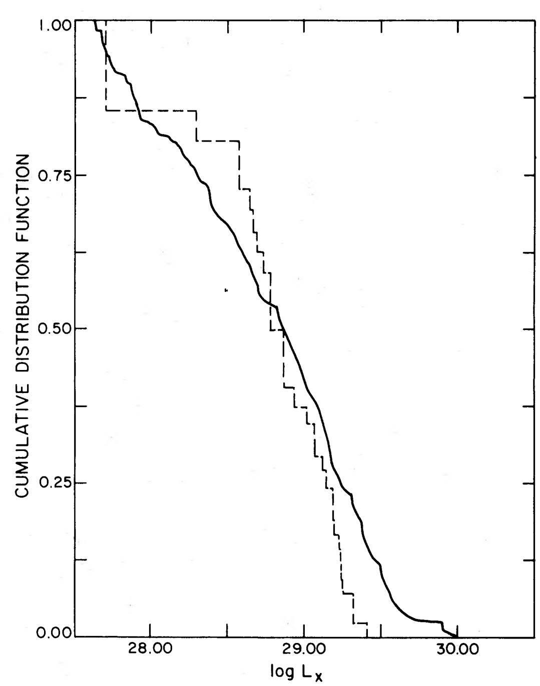

FIG. 7.—Cumulative distribution functions for binary F stars (*dashed histogram*) and for the convolution (*solid histogram*) of the dwarf M star distribution function (Rosner *et al.* 1981) with the single F star distribution function. The proximity of the two curves shows that statistically the binary F stars' X-ray emission can be thought of as a statistically independent mixture of single F star and M star X-ray emission.

implicitly assumed that the (unknown) X-ray luminosity distribution functions for G and K dwarfs are similar to the M star X-ray luminosity distribution function. As far as deducing the properties of the coronae in F stars is concerned, we have demonstrated that any procedure to divide the observed X-ray fluxes in a predetermined matter is likely to produce erroneous results, and that an assessment of how the observed X-ray flux from a multiple stellar system has to be distributed between the different components has to be made on a case by case basis.

d) *Comparison to Previous Work*

It is instructive to compare our results to those obtained Topka *et al.* (1982), who could not distinguish between single stars and binaries because their sample was not as optically well-studied. They find for their sample (18 detections and 37 upper limits) that $(\log L_x)_{\rm mean} = 29.05$ and $(\log L_x)_{\rm median} = 28.44 \pm 0.15$. (Note that Topka *et al.* 1982 erred in estimating the error in the median.) We remark in passing that the bootstrap errors appear to be somewhat larger; this is due to smaller sample sizes and to a systematic underestimate of the true error by the likelihood ratio method in finite (small) sample situations (Schmitt 1984).

The median of the joint distribution function and the mean of the binary distribution function agree quite well with the values quoted by Topka *et al.* (1982); we therefore strongly suspect that the sample used by Topka *et al.* (1982) is contaminated by binaries. An additional bias toward high luminosities in the Topka sample may be due to its preferential sampling of more distant later type F dwarfs, of which there are many more in a magnitude-limited than in a volume-limited sample. As already pointed out by Topka *et al.* (1982), detections of faint distant stars will result in high X-ray luminosities, given observations of not too different sensitivity; the upper limits obtained in this fashion are also relatively high and cannot sufficiently reduce the large weight of the high luminosity tail contribution.

We therefore conclude that—for studies of coronal parameters and their correlation with other stellar parameters—multiplicity *is* important, despite Walter's (1983) claim that it is only important insofar as it leads to rapid synchronous rotation in close systems by tidal coupling. (To the contrary, the case for synchronous rotation can be made for only a few of the stars in our sample, and we are nevertheless forced to the above conclusion.) Walter's (1983) procedure of assigning all the X-ray flux to the earlier type, if the mass ratio is significantly different from unity in systems with known orbital parameters, can lead to substantial errors (cf. the case of HR 1983). Any study that does not carefully distinguish between single and binary stars on a case by case basis, can yield unreliable results.

e) *Correlation with Rotation*

As we shall discuss in detail in § IV, we believe that sample stars with $B-V \geq 0.2$, and possibly even all of our sample stars, possess coronae, indicating the presence of subphotospheric convection zones in these stars. For later type stars, i.e., for G, K and M type dwarfs, X-ray emission as measured by total X-ray luminosity or X-ray surface flux, and rotation as measured by equatorial velocity or period are well correlated (Pallavacini *et al.* 1981; Walter 1982), although the exact functional relationships of these correlations are somewhat controversial. In Figure 8 we plot $v \sin(i)$, the measured projected equatorial rotation velocities, versus X-ray luminosity L_x for all single sample stars for which $v \sin(i)$ measurements are available [21 detections in both L_x and $v \sin(i)$, 43 upper limits in L_x with detections in $v \sin(i)$, one detection in L_x with upper limit in $v \sin(i)$, and two upper limits in both L_x and $v \sin(i)$]. No obvious correlation between $\log L_x$ and $\log v \sin(i)$ seems to be present in our sample, confirming the findings of Pallavacini *et al.* (1981), whose conclusions were based on a far smaller sample. With the dashed line in Figure 8 we also plot the relationship $L_x \approx 10^{27} [v \sin(i)]^2$, the linear regression of $\log L_x$ on $\log v \sin(i)$ for the sample of late-type stars studied by Pallacacini *et al.* (1981).

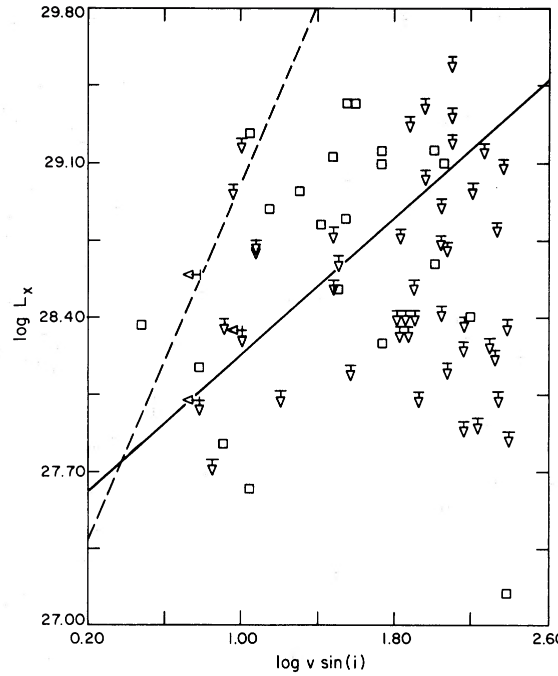

FIG. 8.—X-ray luminosity (L_x) vs. projected equatorial rotation velocity [$V \sin(i)$] for all single stars in our sample for which rotation velocity measurements are available. Boxes indicate stars for which both X-ray and rotation velocity measurements are available; arrows (pointing down- and/or leftward) indicate upper limits. The dashed curve represents the relation $L_x \approx 10^{27} [v \sin(i)]^2$ derived by Pallavacini *et al.* (1981); the solid curve represents the regression curve $\log L_x = 27.91 + 0.36 \log v \sin(i)$ (see text).

In order to compute the formal correlation coefficient including the information contained in the upper limits (which comprise almost 70% of our sample), we calculate the (binned) maximum likelihood distribution function of the single star sample in $\log L_x$ and $\log v \sin(i)$ with a technique described by Schmitt (1984), from which the correlation coefficient r and its error can be computed. For the full sample, we find $r = -0.33$; however, as shown by the bootstrap distribution of r (obtained from 250 bootstrap replications and plotted in Fig. 9; see Schmitt 1984), this (anti)correlation is not significant, since the case $r = 0$ is within the 1 σ errors. Hence we conclude that for the full single star sample no correlation of L_x with $v \sin(i)$ is present.

This lack of correlation does of course not come unexpectedly, since many of the fast rotating A stars were either not seen, or only seen at low levels of X-ray emission. Restricting ourselves to a sample excluding these fast rotators, we might expect to find some correlation between L_x and $v \sin(i)$. This is indeed the case for the single stars with $0.3 \leq B-V \leq 0.5$ [18 detections in both L_x and $v \sin(i)$, 13 upper limits in L_x and detections in $v \sin(i)$, one detection in L_x and upper limit in

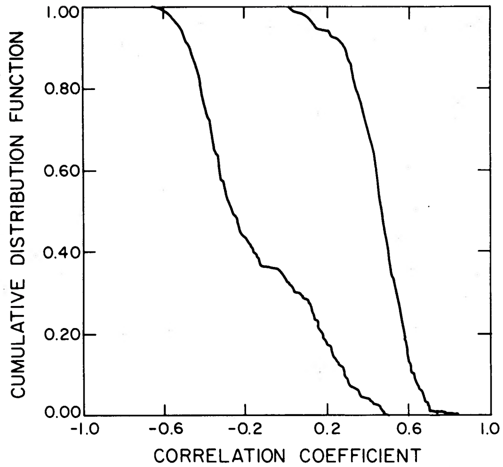

FIG. 9.—Cumulative distribution functions of the bootstrap distribution (see text) of the correlation coefficient between L_x and v sin (i) (defined in the text) for the full sample of single stars (*left curve*) and for single stars in the color range $0.3 \leq B-V \leq 0.5$ (*right curve*).

v sin (i), and two upper limits in both L_x and v sin (i)]. Going through the same procedures as above, we find a correlation coefficient $r = 0.44$, which is significant as the bootstrap distribution of r (shown in Fig. 9, *right curve*) shows. The linear regression of this sample of stars is given by log $L_x = 27.46 + 0.77$ log [v sin (i)] (solid line in Fig. 8). This is incompatible with the linear regression for the later type stars as derived by Pallavacini *et al.* (1981); hence, we conclude that the X-ray luminosity of single stars in the range $0.3 \leq B-V \leq 0.5$ does *not* depend on rotation in the same way as the X-ray luminosities of later type stars do.

A possible interpretation of the increase in correlation between L_x and v sin (i) and slope of the linear regression of log L_x on log v sin (i), noted already by Walter (1983), characterizes the F stars as "transition region" stars (in the H-R diagram) with the onset of dynamo activity somewhere around spectral type F5. However, in this fashion the true meaning of any correlation remains unclear, and almost nothing has been accomplished from a physical point of view. Clearly, if we think of the same mechanism responsible for the observed activity in F through M stars, we should find correlations of stellar parameters throughout this range; we shall discuss such a possible relationship in § IV.

IV. DISCUSSION AND CONCLUSIONS

a) *X-Ray Emission from Single A Stars*

Only four single stars, or rather four stars not known to be binaries, have been detected in the color range $0.1 \leq B-V \leq 0.3$; two of those detections (HR 1014 and HR 7160) are serendipitous sources and suspected to be binaries; the other two (pointed) detections are α Hyi, a very rapidly rotating [v sin (i) = 153 km s^{-1}; Hoffleit 1982], F0 V star with $B-V = 0.28$ at a distance of 20 pc, and α Aql (Altair), also a very rapidly rotating [v sin (i) = 180 km s^{-1}; Hoffleit 1982] A7 V star with $B-V = 0.22$ at a distance of 5 pc.

The star α Hyi has been observed for approximately 2.7 ks, unfortunately at a very low gain setting (20% below nominal). The X-ray spectrum of α Hyi is very soft; in fact, the source was detected only in the soft pulse height channels. However, due to the paucity of counts (only about 20 counts are attributable to α Hyi) no detailed temperature analysis can sensibly be carried out.

Altair, on the other hand, was observed for 11 ks in the IPC (see Golub *et al.* 1983 for more details), at a count rate of ~30 counts ks^{-1} and at very low X-ray temperature; Altair was also observed for about 5.9 ks in the HRI at a count rate of 26 counts ks^{-1}. These long pointings together with the proximity of Altair play a pivotal role for the interpretation of the observed X-ray emission from all A and early F type stars.

For this purpose, it is instructive to recall all *Einstein Observatory* X-ray observations for other nearby (i.e., $d < 10$ pc) A type stars. The relevant data are summarized in Table 2; the data for Sirius and Vega are taken from Golub *et al.* 1983, and the data for Fomalhaut from Caillaut (1983). Note in this context that IPC pointings of Sirius are available; however, due to the limited spatial resolution of the IPC, any images of Sirius A and B appear merged.

It is puzzling that all the HRI pointings resulted in detections, whereas only Altair could be seen in the IPC, but not Vega nor Fomalhaut. Golub *et al.* (1983) argue that this could be due to the softness of the X-ray spectra of these sources as evidenced for example by α Hyi and α Aql, noting that the HRI is more sensitive to soft photons, i.e., with energies less than 0.1 keV, than the IPC. Furthermore, it is remarkable that the HRI count rates for Vega, Sirius, and Altair, when scaled to the same distance, differ only by a factor of 4, which lead Golub *et al.* (1983) to the conclusion that Altair, together with Sirius and Vega, belongs to the early-type stars with regard to its X-ray properties, i.e., its X-ray emission is characterized by $L_x/L_{\rm bol} \approx 10^{-7}$.

In Appendix B we show that the counts observed from Sirius A and Vega in the HRI are very likely to be due *entirely* to UV contamination from photospheric emission, and hence the X-ray luminosities for Sirius A and Vega, as reported by Golub *et al.* (1983), should be replaced by upper limits at least one order of magnitude lower, i.e., log $L_{x,\,\rm Vega} < 26.6$ and log $L_{x,\,\rm Sirius\,A} < 25.6$. Thus the HRI observation of Vega is completely consistent with the upper limit obtained in the IPC, and the only remaining inconsistency concerning the X-ray emission from Vega is the rocket experiment by Topka *et al.* (1979), who report a detection of Vega in a 5 s pointing yielding 7 counts; however, in our opinion these authors do not con-

TABLE 2

EINSTEIN OBSERVATIONS OF NEARBY A TYPE STARS

Name	Sp	$B-V$	HRI Counts ks^{-1}	HRI Counts ks^{-1} d^{-2}	IPC Counts ks^{-1}	S/B
Vega	A0 V	0.00	13	853	<3.4	S
Sirius A	A1 V	0.00	28	204	n.a.	B
Fomalhaut	A3 V	0.09	n.a.	n.a.	<6.9	S
Altair	A7 V	0.22	26	650	30	S

vincingly rule out the possibility of UV contamination. Note in this context that the IPC's used for Topka *et al.*'s (1979) rocket flight and for the *Einstein Observatory* were not identical.

On the other hand, the X-ray observations of Altair, the nearest A7 V star, *cannot* be explained by UV contamination. First, Altair was seen in the IPC at a count rate of ~ 30 counts ks^{-1}; the IPC has essentially no sensitivity to UV or XUV radiation. Second, the HRI data can also not be explained by UV contamination: In Kurucz's (1979) model atmospheres the UV flux decreases rapidly with decreasing effective temperature; in his models with $T_{eff} = 8400$ K the flux at $\lambda \approx 1600$ Å is lower by approximately a factor of 20 than the model for Vega ($T_{eff} = 9400$ K). Hence we estimate that at most 1 count ks^{-1} of the observed 26 counts ks^{-1} for Altair can be attributed to UV.

We therefore conclude that the counts observed from Altair in the IPC and HRI are due to photons at X-ray rather than UV energies, and that Altair's total X-ray luminosity is *at least* an order of magnitude larger than the X-ray luminosities for Sirius A and Vega; hence Altair's X-ray properties are quite different from those of other nearby A stars of somewhat earlier spectral type, and we think—as we shall substantiate in § IV*c*—that the observed X-rays from Altair originate in a corona, heated by magnetic fields produced by a dynamo process similar to the Sun's. On the other hand, any X-ray emission from stars of spectral type around A0, i.e., from stars like Sirius and Vega, is too low to be detectable with the sensitivity of the *Einstein Observatory*. Therefore, the relationship $L_x/L_{bol} \approx 10^{-7}$ does not hold for A type stars in contrast to the conclusions by Pallavacini *et al.* (1981).

b) F Stars and the Onset of Dynamo Activity

As regards the *presence* of X-ray emission from the single A7 V dwarf Altair and the single F0 V dwarf α Hyi, and the *absence* of detectable X-ray emission from the A0 V dwarfs Sirius and Vega, and the rapid increase of both L_x and L_x/L_{bol} over a relatively narrow range of colors, it seems reasonable to assume that convection zones and, employing the solar analogy, magnetic fields, are present in Altair and α Hyi to heat the observed X-ray emitting coronae. It is difficult to determine the precise critical value of $B-V$, at which this transition occurs; it is certainly not greater than 0.3, but may in fact be as low as 0.22 or smaller, in agreement with the results obtained by Böhm-Vitense (1978), who finds disagreement between radiative equilibrium models and continuum observations only for the fast rotators in the color range $0.1 < B-V < 0.22$ (!). Note that the data point at $B-V = 0.22$ and $\log L_x = 27.14$ (in Fig. 1) represents an 11 ks pointed observation of Altair (A7 V), which is also claimed by Blanco, Catalano, and Marilli (1980) to show chromospheric emission as observed in the Mg II and K line. The data also do not allow us to decide whether the transition to large values of X-ray emission occurs smoothly or abruptly.

Our claim that magnetic dynamos exist in stars as early as A7 is new and may arouse controversy. Current wisdom has it that magnetic dynamos cannot be sustained in stars of spectral type earlier than about F6 (see, for example, Durney and Latour 1978); consequently, Walter (1983) has invoked—for stars earlier than about $B-V = 0.45$—primordial magnetic fields trapped in the radiative core, which then manifest themselves in an unspecified way. If stars as early as A7 have coronae, they should also have winds—similar to the Sun's wind—which transport angular momentum very efficiently in the presence of magnetic fields and cause rapid spin-down; this is in fact precisely Durney and Latour's (1978) argument to explain the observed break in the rotation velocities near spectral type F5. For those stars that are not young, but have not spun down and still emit X-rays, the problem arises as to why they maintain their fast rotation and do not follow the rotation-activity relations observed for later type stars despite the asserted presence of dynamo related activity.

The rotation-activity relations will be discussed in § IV*c*; the lack of spin-down can be explained with Durney and Latour's (1978) own arguments: In stars of spectral type around F0 the Rossby number R, given by and related to the dynamo number N_D by

$$R \approx \frac{P}{T_{\rm conv}} \approx N_D^{-1/2} , \qquad (4.1)$$

where P denotes the period and $T_{\rm conv}$ the convective turnover time, cannot become small without break-up of the star. Hence the dynamo number cannot become too large, and if, as Durney and Latour (1978) assert, the generated magnetic fields are proportional to the dynamo number, the angular momentum loss in the wind is—despite its sensitive dependence on magnetic fields—not sufficient for any appreciable spin-down during a stellar lifetime exactly because the spin-down time scale as calculated by Durney and Latour (1978) depends very sensitively on stellar mass.

c) Evidence for Dynamo-related Activity

The lack of correlation between soft X-ray luminosities with rotation rates or equatorial rotation velocities for F type stars (as already noticed by Pallavacini *et al.* 1981) and the high level of X-ray emission when compared to the bolometric luminosity puts this group of stars into a seemingly sharp contrast to the G, K, and M type stars, whose X-ray luminosities and X-ray surface fluxes correlate well with other rotational indicators (Pallavacini *et al.* 1981; Walter 1982), as well as the O and B type stars, whose X-ray luminosities correlate well with their bolometric luminosities (Pallavacini *et al.* 1981).

The correlation of X-ray luminosities with rotational indicators is usually interpreted as supporting a picture of dynamo induced stellar activity in G, K, and M type dwarfs. However, the absence of such correlations—as demonstrated in Figure 8—need not imply the absence of *solar-like* dynamo activity in these stars as asserted by Walter (1983). As pointed out, for example, by Noyes *et al.* (1984), the important quantity, from a theoretical point of view, is the Rossby number R (see eq. [4.1]); Noyes *et al.* (1984) showed that the ratio of the Ca II H–K flux, corrected for photospheric contributions, to the total bolometric flux is well correlated to the Rossby number R for a sample of lower main-sequence stars with known periods and mean Ca II H–K emission levels.

For our sample of F stars, only $v \sin(i)$, rather than period measurements, are available; in order to obtain the Rossby number we hence set

$$R = \frac{\pi^2}{2} \frac{r}{v \sin(i) T_{\rm conv}} , \qquad (4.2)$$

where r denotes the stellar radius. We use the values given by Allen (1973) to obtain mass and radius estimates from the color $B-V$, and we use Gilman's (1980) calculations to estimate convective turnover times as a function of mass and α, the ratio of mixing length to pressure scale height.

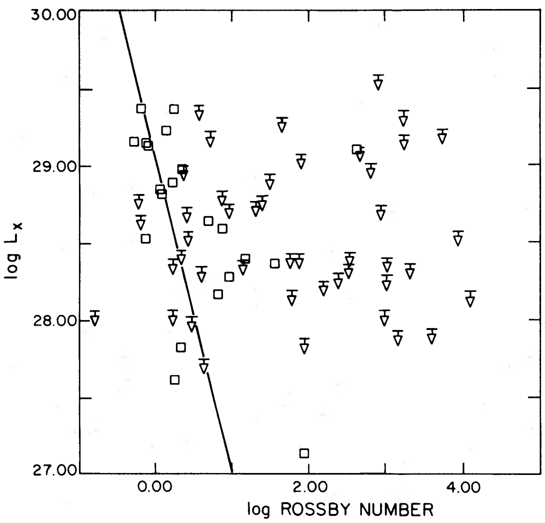

FIG. 10.—Plot of X-ray luminosity vs. Rossby number for all single stars (using eq. [4.2]). The solid line is an eyeball fit under the assumption that L_x is proportional to the dynamo number (see text).

In Figure 10 we plot the logarithmic X-ray luminosities as a function of the logarithm of the Rossby number, calculated according to equation (4.2) for the case $\alpha = 2$ (α is ratio of mixing length to pressure scale height), for those single stars in our sample, for which rotation measurements are available. Note that the same sample that shows essentially no correlation with rotation as measured by $v \sin(i)$, does show some correlation with Rossby number in the sense that high X-ray emitters tend to have smaller Rossby numbers as expected. We also notice that the obtained upper limits either fall within the scatter or lie considerably above the line $\log L_x = 29–2 \log R$, also shown in Figure 10, whose significance is discussed below. Incidentally, the outlying data point at $\log R \approx 2.6$, $\log L_x \approx 29.2$ is the star HR 7160, which we suspect to be binary as discussed in § III*b*. We also remark in passing that a plot of $\log(L_x/L_{bol})$ versus log R shows a similar correlation as the one between $\log L_x$ and log R as shown in Figure 10.

Hence the data are consistent with a correlation between X-ray luminosity and Rossby number; however, we shall interpret it more in a qualitative, rather than quantitative fashion for the following reasons: First, due to errors in the assumed source distances and X-ray temperatures, the X-ray luminosities used may be uncertain by a factor of 2 or so; second, our X-ray luminosities are snapshot values rather than long-term averaged values as used by Noyes *et al.* (1984); third, no periods, but only $v \sin(i)$ measurements, are available, which introduces viewing geometry and radius as yet other unknowns; fourth and most important, our sample covers only a small range in stellar mass, but the computed theoretical convective turnover times depend extremely sensitively on mass in the parameter range considered (Gilman 1980). Nonetheless, despite all these uncertainties the applied corrections all seem to go into the right direction.

The correlation of X-ray luminosity with Rossby number (if real), may provide the type of correlation alluded to in § III*d*. Noyes *et al.* (1984) already commented that a simple relationship between Ca II H–K flux ratios and Rossby number is quite surprising, since the observed emission is the result of a complex transfer process of magnetic fields from the bottom of the convection zone to the surface, the build-up and final release of magnetic stresses, leading to chromospheric and coronal heating, all of which may depend on other stellar parameters such as mass or chemical composition. It would indeed be truly remarkable, if observables like Ca II H–K flux ratios and/or soft X-ray fluxes depend only on the Rossby number. In this context we wish to point out that a correlation between Rossby or dynamo number with L_x need not contradict the usually quoted rotation-activity relations; for example, if we postulate that $L_x \propto N_D$ similar to Durney and Latour (1978), we find from Figure 10 that $\log L_x = 29–2 \log R$ to good approximation. Replacing R with equation (4.1), we obtain

$$\log L_x = 27.6 + 2 \log [v \sin(i)] - 2 \log r + 2 \log T_{\rm conv} . \tag{4.3}$$

For late-type dwarfs, radii and turnover times change only little along the main sequence (Gilman 1980); using solar values for radius and turnover time, we may think of equation (4.3) as essentially identical to the relation empirically found by Pallavacini *et al.* (1981), especially in view of the considerable uncertainty in the calculation of the turnover times. Obviously, in order to test this hypothesis, a larger sample of stars spanning a larger range in mass and Rossby numbers needs to be studied.

V. SUMMARY

We summarize our main results and conclusions as follows: We have conducted an X-ray survey of bright main-sequence dwarfs and subgiants in the color range $0.1 \leq B-V \leq 0.5$ and find that the X-ray properties of single and binary stars in our sample differ significantly. We interpret this difference as being due to multiple X-ray sources. For the binaries, no intrinsically enhanced X-ray emission (for example, via synchronous rotation) has to be assumed; the X-ray emission from F type binaries can simply be explained as emission from a spatially unresolved, statistically independent mixture of X-ray sources consisting of a single F star and a late-type dwarf. We construct maximum likelihood X-ray luminosity distribution functions for single stars and binaries in various color ranges. Over the color range considered, the X-ray luminosities increase rapidly, an effect we interpret as being due to a dependence of L_x on Rossby number, and we argue that all of the *detected* (single) stars in our sample are convective and the sites of magnetic dynamos. This interpretation finds support by the absence of any correlation of X-ray luminosity with rotational indicators, and the fact that X-ray emission (at presently detectable levels) appears to be absent in stars with $B-V \approx 0.0$.

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APPENDIX A

SURVEY PROCEDURES

I. DETECT ALGORITHM AND FLUX CONVERSION

The IPC background varies with position because of mirror vignetting, spatial instrument gain variations, and shadowing from the entrance window support structure (ribs); thus, the use of a global background for background subtraction purposes can lead to significant errors. Furthermore, the detector point response function, i.e., the accuracy with which the position of an incident photon coming from a point source can be located in the detector, is dependent on pulse height (PH) channel. In REV1 IPC reprocessing (Harnden 1982) all these effects are accounted for by constructing an exposure map to calculate the effective exposure at each source position, and a gain map, to take into account gain variations, and by measuring source and background counts in a detect and border cell (surrounding the detect cell), and by correcting for source photons "scattered" out of the detect cell. If the probability α that a source photon falls into the detect cell, and the probability β that a source photon falls into either detect or border cell, are known, it is straightforward to compute the source strength S and background strength B (assumed to be uniform over detect and background cells) from the counts in the two cells. Since the energies corresponding to individual PH channels also vary with varying gain, a source at fixed X-ray temperature will appear in different PH channels, and therefore the probabilities α and β will also vary with gain.

In order to convert IPC count rates to apparent fluxes, an incident spectrum has to be assumed; for flux conversion purposes we assume that all the sources in our sample emit thermal line spectra at a temperature log $T = 6.25$. A preliminary temperature analysis of the IPC PH spectra showed that many (but not all) of the sample stars' spectra are consistent with this assumption; a detailed temperature analysis, however, has to await the availability of REV1 processed data. As already discussed, varying gain shifts the energy boundaries of the PH channels, and thus the counts received from a nonvariable source would actually appear to be varying with gain. Therefore it is customary to choose a certain energy band (say, 0.2–4.5 keV), and use only those pulse height channels for analysis which include the desired energy band. For soft sources with X-ray temperatures of log $T = 6.3$ or less, this procedure is disadvantageous, since it disregards the photons "scattered" into the bottom PH channels; particularly at high gain settings, a significant percentage ($\sim$30%–40%) of the total number of observed events remains unused. Therefore we decided to use the total number of counts regardless of the gain setting and correct for the instrument gain with a gain varying flux conversion factor.

The IPC loses sensitivity very rapidly below about 0.2 keV (see Giacconi *et al.* 1979); on the other hand, the total flux emitted from an optically thin gas in collisional equilibrium increases with decreasing temperature (in the temperature range of interest). Choosing the energy band between 0.15 and 4.0 keV gives a conversion factor, which changes only by a factor of 2, when going from log $T = 6.3$ to log $T = 5.8$, whereas the conventional choice of the 0.2–4.0 keV energy band gives a conversion factor changing by a factor of 6 in the same temperature range. In Figure 11 we plot the conversion factor (at normal gain) as a function of temperature for several energy bands; the 0.15–4.5 keV band is clearly seen to be the most appropriate choice for the sources of interest.

II. SOURCE RECOGNITION

We use a simple hypothesis test to decide whether a source has been detected or not. Adopting the null hypothesis that no sources are present in both detect and border cells, the counts in these cells should be derived from similar parent distribution, i.e., Poisson distributions, whose means scale like the areas of the two cells. Let c and q be the counts in detect and border cells, respectively, and

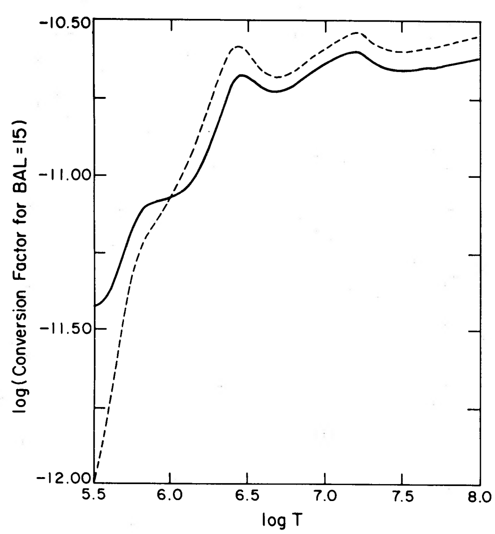

FIG. 11.—Plot of IPC count rate-to-energy flux conversion factor vs. temperature for the 0.15–4.0 keV (*solid curve*) and 0.2–4.0 keV (*dashed curve*) passbands

w_c and w_q the areas of detect and border cells, respectively; it is then easy to show that the estimate for the background per unit area, λ_B,

$$\lambda_B = \frac{c + q}{w_c + w_q} \tag{A1}$$

is a maximum likelihood (ML) estimator for λ_B. The quantity

$$\chi^2 = \frac{(c - w_c \lambda_B)^2}{w_c \lambda_B} + \frac{(q - w_q \lambda_B)^2}{w_q \lambda_B} \tag{A2}$$

is then (asymptotically) distributed like a χ^2 distribution with one degree of freedom (von Mises 1964). If the observed value of χ^2 exceeds some suitably chosen threshold $\chi^2{}_{\rm th}$, we reject the null hypothesis (i.e., we have found a source).

APPENDIX B

UV SENSITIVITY OF THE HRI

With data kindly supplied to us by P. Henry and M. Zombeck (1983, private communication), we reanalyzed the effective area for the HRI in the waveband 1000–2000 Å. In Figure 12 we plot the effective HRI area as a function of wavelength in this waveband (*solid line*). The dashed lines represent the uncertainties in the effective areas only due to the uncertainty in the thickness of the Parylene N coating (nominally 7200 Å); additional substantial uncertainties arise from the uncertainty in the aluminum thickness, errors in our analytical fits to mass absorption coefficients, and quantum efficiencies. In any event, the minimum in the mass absorption coefficient of Parylene N at around 1600 Å leads to a narrow transmission window with a width of about 80 Å and peak effective area of about 10^{-7} cm^2.

Using the effective area, as shown in Figure 12, together with model atmospheres calculated by Kurucz (1979) and assuming a distance of 7.5 pc and a radius of 2.6 $R_\odot$ for Vega, we predict a count rate of 5.5 counts ks^{-1} for Vega. Note in this context that the UV flux emerging from a stellar photosphere is a sensitive function of the assumed metal abundances; for Vega there is good agreement between theory and observation, whereas the models for Sirius A agree rather poorly with the observations, presumably because of abundance anomalies.

The predicted count rate of 5.5 counts ks^{-1} for Vega is entirely due to UV flux around 1600 Å, whereas the observed count rate is 13 counts ks^{-1}; the theoretically predicted count rate depends very sensitively on only the actual thicknesses of both the Parylene N and the aluminum filter, and the amount of oxidization of the latter. In addition, the detector quantum efficiencies are only very poorly known in this waveband. Hence the observed count rate is certainly within the "1 σ" uncertainty of the nominally predicted count rate.

A second argument in support of the hypothesis that the observed HRI counts from Vega (and Sirius) are due to UV contamination can be made by comparing the ratios of the observed HRI fluxes to the ratio of the UV fluxes, a procedure obviously insensitive to calibration uncertainties in any instrument. From Jamai *et al.*'s (1976) TD-1 observations we find for the flux ratio at 1580 Å, the peak in the HRI effective areas, $f_{\rm Sirius}/f_{\rm Vega} = 3.0$ as compared to the ratio of the observed HRI fluxes, $f_{\rm Sirius}/f_{\rm Vega} = 2.2$.

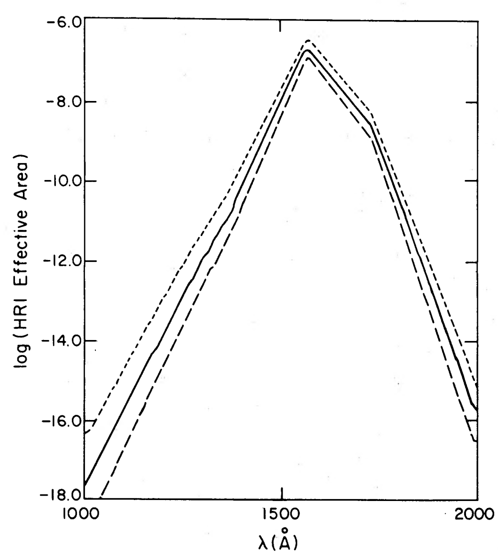

FIG. 12.—HRI effective area vs. wavelength. The solid curve shows the predictions using the nominal filter thicknesses, while the dashed curves indicate the possible variation in effective area due to uncertainties just in the Parylene N filter thickness.

The latter ratio is quite uncertain: Vega's HRI flux has a statistical uncertainty of about 20%, and we estimate the uncertainty in Sirius's HRI flux to be of the order 50% (because of the presence of the nearby strong point source Sirius B). Hence the TD-1 and HRI flux ratios for Sirius and Vega are consistent. In any event, the ratio of the observed TD-1 fluxes at 1580 Å predicts the ratio of the observed HRI fluxes much better than, for example, the ratio of the bolometric luminosities ($L_{\text{bol, Sir}}/L_{\text{bol, Vega}} = 4.0$) or the ratio of the squared distances $[(d_{\text{Sir}}/d_{\text{Vega}})^{-2} = 8.1]$. We therefore conclude that the photons observed from Sirius A and Vega in the HRI are *entirely* due to photospheric UV radiation, and that the *Einstein Observatory* X-ray observations of Sirius and Vega provide no evidence for an X-ray emitting corona around either star.

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