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X-RAY STUDIES OF COEVAL STAR SAMPLES. III. X-RAY EMISSION IN THE URSA MAJOR STREAM

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ABSTRACT

We report the results of a comprehensive survey of X-ray emission from stars known or suspected to be members of the Ursa Major cluster and/or stream. Of the 42 Ursa Major member stars surveyed, 18 were detected as X-ray sources, and spectral analysis was performed for 10 stars with sufficient X-ray counts. We discuss relations between X-ray luminosity, color, and kinematics of our sample stars and comment on the X-ray spectra of the Ursa Major stars in the context of the general problem of stellar X-ray temperatures. We confirm the lack of X-ray–emitting A dwarfs also among Ursa Major members; among stars of later spectral type we find a rather large dispersion in X-ray luminosity. This dispersion cannot readily be explained by contamination with field star interlopers and appears rather to be a property of the Ursa Major X-ray luminosity distribution function.

Subject headings: clusters: open — stars: rotation — stars: X-rays

I. INTRODUCTION

Imaging data from the *Einstein Observatory* (cf. Giacconi *et al.* 1979) have established the ubiquity of stellar X-ray emission in almost all regions of the Hertzsprung-Russell diagram, with the possible exception of late B and early A stars (see, for example, Vaiana *et al.* 1981; Rosner, Golub and Vaiana 1985). For late-type stars (viz., stars of spectral type F, G, K, and M), the two most important factors determining the level of X-ray emission appear to be rotation and age (cf. Pallavicini *et al.* 1981; Walter 1982; Maggio *et al.* 1987; Micela *et al.* 1985, 1988, 1990; Rosner, Golub, and Vaiana 1985 and references therein). Typically, young and/or fast rotating stars show significantly enhanced X-ray emission as compared to old and/or slowly rotating stars, but fast rotation and/or youth do not necessarily imply high levels of activity as measured through X-ray luminosity. For example, the young rapidly rotating Pleiades K dwarfs are as X-ray–luminous as the more slowly rotating G dwarfs (Caillault and Helfand 1985; Micela *et al.* 1985, 1990) contrary to the expectation of the $L_x \propto (v \sin i)^2$ relation. Fast rotating stars in the color range $0.1 < B-V < 0.5$ do not have correlated X-ray luminosity and rotational velocity (Pallavicini *et al.* 1981; Schmitt *et al.* 1985). Furthermore, for field G stars it is next to impossible to disentangle the effects of rotation and age (see Maggio *et al.* 1987).

As a consequence, studies of stellar groups and clusters play a crucial role not only for our understanding of stellar evolution, but also for our understanding of stellar activity as a general astrophysical phenomenon. Members of a stellar group or cluster provide samples of coeval objects in a natural way and can therefore be utilized in an effort to isolate the effects of rotation and age in determining activity levels.

For this reason several stellar clusters have been extensively studied with the *Einstein Observatory*, most notably the Hyades cluster (Stern *et al.* 1981; Micela *et al.* 1988), the Pleiades cluster (Caillault and Helfand 1985; Micela *et al.* 1985, 1990) and various star-forming regions such as the ρ Oph cloud, Chamaleon star-forming region, and the Orion and Taurus-Auriga complexes (see, for example, Ku and Chanan 1979; Feigelson and deCampli 1981; Montmerle *et al.* 1983; Feigelson *et al.* 1987; Walter *et al.* 1988; Feigelson and Kriss 1989).

The Ursa Major group is visually not a cluster comparable to the Hyades or Pleiades clusters; with no conspicuous appearance in the sky, its existence can only be deduced by a statistical study of stellar space motions. It appears to be a stellar stream of unknown extent in which the Sun is immersed. The nucleus of the stream (located in the Ursa Major region) consists only of 15 known members (in the compilation of Roman 1949) in a volume of $10 \times 6 \times 4$ pc^3, thus barely reaching the density of field stars. Unfortunately, the measured parameters of the nucleus stars do not allow an accurate determination of the convergent point (Petrie and Moyls 1953), making the assignment of membership of candidate stream stars difficult and to some extent arbitrary (depending on what membership criteria are chosen).

In order to avoid the traditional ambiguities in assigning Ursa Major membership, Eggen (1958) introduced the Sirius group, which consists of stars whose space motion is parallel to the well-known space motion of the nearby A star Sirius. As an illustration of the problems of kinematic membership assignment, we note that Roman (1949) selected as probable stream members 142 HR stars of 379 stars listed by other authors; Eggen (1960) selected as probable Sirius group members 86

HR stars, of which 62 overlap with Roman's (1949) list. However, despite the problems of assigning the membership of individual stars, it is clear that the Ursa Major/Sirius group exists as a statistical and physical entity. It contains stars presumably younger than the Hyades cluster (Duncan 1981) and is consequently also very interesting from the X-ray point of view.

Walter *et al.* (1984) report *Einstein* measurements of 11 Ursa Major stars (nine detections, two upper limits). The derived X-ray luminosities for these Ursa Major stars span—somewhat surprisingly—more than two orders of magnitude. Walter *et al.* (1984) accordingly argue that the low-luminosity objects in their sample are likely due to contamination by older field stars sharing the Ursa Major group space motion, whereas the high-luminosity objects are interpreted as true group members, with a mean X-ray luminosity larger than that observed in the Hyades cluster. Similar conclusions with respect to field star contamination were reached by Soderblom and Clements (1987) in a study of the ultraviolet emission from Ursa Major stars using the *IUE* satellite.

The purpose of this paper is to provide the most recent presentation of our current knowledge of the X-ray emission in the Ursa Major group utilizing the complete *Einstein* X-ray data in their final reprocessed form. Our sample consists of 42 Ursa Major group members, 18 of which were detected; in addition, we present X-ray spectra for 10 stars with sufficient counting statistics to allow spectral analysis.

II. SAMPLE AND DATA ANALYSIS

a) Sample Definition

In principle, kinematic membership assignment is a straightforward task; given measurements of proper motion, parallax and radial velocity, a star's space velocity can be calculated (see Johnson and Soderblom 1987) and the membership can be assessed by comparing measured and cluster space velocities. In practice this task is complicated by the fact that the observational errors propagate differently into the three space velocity components, and furthermore the space motion of the Ursa Major nucleus cannot be determined very precisely. Roman (1949) computes for each candidate star the position angle of proper motion, the radial velocity, and the cluster parallax assuming that the star shares the Ursa Major nucleus space motion. If computed and observed quantities agree (with the amount of agreement left unspecified), the star is considered a probable stream member.

As a starting point of our X-ray study we considered all stars contained in Roman's (1949) list of Ursa Major cluster members and probable Ursa Major stream members as well as those contained in Eggen's (1958, 1960) list of Sirius group members. We then determined which stars were surveyed with the *Einstein Observatory* either in pointed or serendipitous mode. If a target was observed more than once, we report only the results of the most sensitive observation except for the case of HR 5544, where two observations of about the same quality are available.

Our full sample consists of 42 stars with 40 listed in the Bright Star Catalog (Hoffleit and Jaschek 1984) plus HD 112394 and HD 124752; two stars, HR 5328 and HR 5329, are unresolved by the Imaging Proportional Counter (IPC; Gorenstein, Harnden, and Fabricant 1981). Out of the 40 HR objects, 37 are listed in Roman's (1949) list as probable Ursa Major group members, 24 are listed by Eggen (1960) as probable Sirius group members and 16 stars belong to Roman's (1949) Ursa Major Stream, but not to Eggen's (1960) Sirius group; three stars belong to Eggen's group but not to Roman's. Interestingly, all of these three stars—α Cnc = HR 3572, μ Vel = HR 4216 and δ Del = HR 7928—are listed by Roman (1949) as stars probably not members of the Ursa Major group.

b) Data Analysis

Practically all of our data (except those for the star α CrB) were obtained with the *Einstein Observatory*; for some sample stars the High Resolution Imager (HRI) was used, but the majority of objects was observed with the IPC, which provided spectral coverage between 0.16 and 4.5 keV with a spectral resolution of $\Delta E/E \sim 1$ at 1 keV. The HRI covered the same band pass, albeit with a differing efficiency and no spectral resolution.

We utilized the final IPC reprocessing software (Rev-1; see Harnden *et al.* 1984 and Micela *et al.* 1988 for details) in our analysis. The so-called MDETECT count rates, obtained with a global background model in the broad *Einstein* band (0.2–3.5 keV), were used whenever available, but if no global background model could be constructed, we used the so-called LDETECT count rates (also for the broad band) for which background was determined from data in the immediate vicinity of the source. Rev-1 processing applies corrections for spatial and temporal gain variations, vignetting, and detection-cell efficiency in order to give the effective count rate (with related error) for each detected source. The existence of a nonzero Rib and Edge COde (RECO) flags the possibility that a derived source rate may have been affected due to shadowing of the source by the IPC entrance-aperture support structure (see Micela *et al.* 1988 for more detailed discussion).

IPC fluxes, in the 0.16–4.0 keV bandpass, were generally obtained by applying the "standard" conversion of 2×10^{-11} ergs cm^{-2} count^{-1}. This value was used to allow easy comparison of present results with previous published data and is correct for a source temperature of $\gtrsim 3 \times 10^6$ K, with negligible hydrogen column density absorption. For those sources observed with sufficiently large signal-to-noise ratio to allow spectral analysis, an improved flux estimate based on the spectral fit results was also obtained. The derived X-ray temperatures (see § IV*b*) are in the range for which the "standard" correction is sufficiently accurate (see Appendix in Schmitt *et al.* 1985). For the HRI, we used a conversion factor of 4×10^{-11} ergs cm^{-2} count^{-1}, which is appropriate for relatively soft stellar X-ray sources (cf. Harris and Irwin 1984). We estimate that the uncertainties in the counts to flux conversion are typically of the order $\sim$25% in those cases where no further spectral information is available. For the 10 stars for which Walter *et al.* (1984) reported X-ray luminosities, we have verified that our X-ray luminosities differ in most cases by less than a factor of 2. In three cases where the difference is larger (HD 39587, HD 105452, and HD 131156), the apparent discrepancies can easily be explained by the fact that the final IPC processing, which incorporated an improved algorithm for rejecting data contaminated by solar X-rays scattered in Earth's atmsophere, rejected a substantial fraction ($\approx \frac{1}{3}$–$\frac{1}{2}$) of the data available to Walter and collaborators.

III. RESULTS

a) X-Ray Luminosity and Color

Table 1 reports the basic results of this paper. In columns (1) and (2) we give HR and HD numbers of our sample stars,

TABLE 1

X-Ray Results for Ursa Major Cluster Stars

HR (1)	HD (2)	Sequence (3)	Count Rate (10^3 counts s^{-1}) (4)	Method (5)	log L_X (0.16–4.0 keV) (ergs s^{-1}) (6)
271	5516	I 4940	162.3 ± 4.0	M	29.68
290	6116	I 2255	<4.7	L	<28.48
797	16861	I 7510	<3.6	L	<28.88
919	18978	I 7525	<3.4	L	<27.36
1448	28978	I 351	<0.95	L	<28.26
1666	33111	I 5471	83.8 ± 5.4	M	28.90
1971[a] ...	38104	I 483	<9.4	L	<28.78
1982	38392	H 5481	48.0 ± 5	...	28.43
1983	38393	H 5481	6.4 ± 1.9	...	27.56
2047	39587	I 4347	271.6 ± 15.6	M	28.78
2491	48915	H 946	<12.1	...	<26.61
3064	64096	I 10669	5.3 ± 2.0	M	27.51
3391	72905	I 6964	178.2 ± 4.4	M	28.92
3572	76756	I 4895	<5.2	L	<28.38
3903	85444	I 7607	108.7 ± 7.0	M	29.77
3998	88355	I 5367	9.2 ± 3.4	M	28.43
4216	93497	I 4448	689.0 ± 31.0	L	30.17
4623	105452	I 5538	66.6 ± 5.8	M	28.49
4865	111397	I 7018	<4.3	L	<28.73
4867	111456	I 7913	116.3 ± 5.9	M	29.20
4905	112185	I 2240	<4.6	L	<27.64
... .	112394	I 8957	<4.9	L	<27.87
5020	115659	I 7682	33.0 ± 3.4	M	29.03
5054	116656	H 4473	<2.2	...	<27.66
5055	116657	H 4473	6.0 ± 1.6	...	28.10
5105	118022	I 840	<4.9	L	<28.41
5328[b] ...	124674	I 271	<15.0	L	<28.45
5329[b] ...	124675	I 271	<15.0	L	<28.45
... .	124752	I 10429	<6.0	L	<27.88
5343	124953	I 4450	<6.6	L	<28.60
5365	125451	I 9705	52.0 ± 6.8	L	29.42
5544	131156	I 10418	624.8 ± 27.6	L	28.79
5727[c] ...	137107	I 10404	13.1 ± 2.9	M	27.90
5728[c] ...	137108	I 10404			
5763	138481	I 3089	<3.1	L	<28.27
5793	139006	EXO	<0.84	...	<28.59
6117	148112	I 4890	<2.85	L	<27.59
6556	159561	I 842	19.7 ± 5.3	M	28.02
7928	197461	I 8923	<4.4	L	<28.52
8207[d] ...	204139	I 7798	<17.0	L	<30.02
8410[e] ...	209625	I 10129	<12.1	L	<29.15
8454	210459	I 9029	<12.4	L	<29.44

[a] Observed with Ribs and Edges COde (RECO; see text) 1008.
[b] Not separated by IPC; observed with RECO 200.
[c] Not separated by IPC.
[d] Observed with RECO 1006.
[e] Observed with RECO 400.

respectively; column (3) reports the instrument used (I indicates the IPC and H, the HRI) and *Einstein* sequence number. In most cases we used IPC data, for a few stars the HRI was used and in one case (α CrB) the EXOSAT Low Energy experiment (see de Korte *et al.* 1981) was used. In column (4) we indicate the derived X-ray count rate (per 1000 s) or its 3 σ upper limit. The detection flags in column (5) apply to IPC data only and indicate the detection method used (M for MDETECT, L for LDETECT; cf. Harnden *et al.* 1984). In column (6) we report the 0.16–4.0 keV X-ray luminosity (log ergs s^{-1}), computed with the distance estimate given in Table 2.

In Table 2 we report auxiliary data used for our data interpretation. For each star identified by its HD number we give the adopted distance (col. [2]), $B-V$ color (col. [3]), and spectral type (col. [4]). In subsequent sections we will require the space velocities U, V and W which are given in columns (5), (6), and (7); note that we are using a coordinate system with the positive U-axis pointing toward the Galactic center. In column (8) we give the modulus of the velocity difference between the star and the cluster nucleus adopted to be $U_{nuc} = 13.9$ km s^{-1}, $V_{nuc} = 1.5$ km s^{-1}, and $W_{nuc} = -9.4$ km s^{-1} following Eggen (1983).

In Figure 1 we show the dependence between X-ray luminosity and color for all our sample stars in graphical form. We note in particular the abundance of upper limits in the color range $0.0 < B-V < 0.3$. Most stars redder than $B-V \sim 0.4$ are detected with X-ray luminosities spanning more than two orders of magnitude. This is in marked contrast to the Hyades and Pleiades surveys where the dynamic range of detected X-ray luminosities is smaller. We note in this context that for each of the latter two surveys, the X-ray luminosity threshold was fairly uniform across individual surveys since the exposure time and distance of each cluster star were rather similar;[1] this is not the case of the Ursa Major group where the threshold X-ray luminosity varies over orders of magnitude.

Table 3 contains a detection and upper limit summary by spectral type. Of the 42 objects included in the sample, 18 were detected. As can be seen from Table 3, the sample contains no M dwarfs and only a small fraction of K dwarfs; therefore the optical Ursa Major group sample is severely incomplete at faint (optical) luminosities and many group members of spectral type K and M must have been missed in the optical surveys unless the Ursa Major stars obey an anomalous mass function. The detection rate is fairly high among the G and F stars. In Figure 2 we plot the cumulative X-ray luminosity distribution functions (in the 0.16–4.0 keV passband; derived using detections and bounds via the Kaplan-Meier estimate, cf. Schmitt 1985), for main-sequence stars and giants in the full color range and in the color range $B-V \geq 0.3$; note that this distribution function has been constructed taking into account the information contained in the upper limits as well as detections. The mean of the logarithmic X-ray luminosities for the giants and main sequence stars redder than $B-V = 0.3$ is found to be log $L_X = 29.02 \pm 0.25$ and log $L_X = 28.41 \pm 0.17$, respectively.

b) A-Type Stars

The X-ray detection rate is low for A dwarfs, as found previously for field dwarf A stars (cf. Schmitt *et al.* 1985): only one (HD 116657) of 15 A dwarfs was detected. Two of four A giants were detected in our sample.

Two detections (HD 116657 and HD 159561) were reported by Vaiana *et al.* (1981) and Golub *et al.* (1983), but the detection of HD 33111 is new. A crucial question to ask is whether these detections really pertain to the A stars or are due instead to fainter main sequence companions (cf. Golub *et al.* 1983). HD 116657 (= ζ UMa B) is a metallic line star and a spectroscopic binary and shows X-ray emission despite its long period (cf. Cash and Snow 1982). HD 159561 = α Oph is reported by Lippincott and Wagman (1966) as an astrometric binary with a probable solar-like main-sequence companion at a distance of ∼0″.5, although McAlister (1978) failed to resolve this sytem with speckle interferometry. HD 33111 = β Eri is apparently

[1] Despite the small dynamic range, more than half of the Pleiades stars and essentially all Hyades G stars were detected in X-rays, thereby enabling those surveys to determine good X-ray luminosity functions.

TABLE 2

OPTICAL PROPERTIES OF URSA MAJOR CLUSTER STARS

HD (1)	Distance (pc) (2)	$B-V$ (3)	Spectral Type (4)	U (km s^{-1}) (5)	V (km s^{-1}) (6)	W (km s^{-1}) (7)	ρ (km s^{-1}) (8)
5516..........	35	0.94	G8 IIIb	11.29	−6.72	1.69	13.72
6116..........	52	0.16	A5m	2.18	5.89	−3.00	13.28
16861..........	94	0.06	A2 V	6.28	3.59	−13.98	8.67
18978..........	17	0.16	A4 IV	13.48	7.58	2.49	13.06
28978..........	90	0.05	A2 Vs	10.71	4.16	−5.37	5.17
33111..........	20	0.13	A3 III	13.27	3.26	−6.78	2.88
38104..........	52	0.03	A2 VpCr	7.57	4.30	−3.41	8.43
38392..........	8	0.94	K2 V	16.83	5.78	−10.33	5.74
38393..........	8	0.47	F6 V	16.83	5.78	−10.33	5.74
39587..........	9.6	0.59	G0 V	13.64	3.00	−8.68	1.59
48915..........	2.7	0.00	A1 Vm	14.44	−0.40	−11.66	3.47
64096..........	16	0.60	G0 V:	25.35	0.17	−19.51	16.10
72905..........	14	0.62	G1.5 Vb	9.13	−2.68	−9.13	5.84
76756..........	40	0.14	A5m	15.79	0.82	−5.09	4.86
85444..........	48	0.92	G7 III–IIIb	12.23	7.77	−9.50	6.30
88355..........	35	0.46	F7 V	13.12	2.14	−11.85	2.81
93497..........	30	0.90	G5 III+G2 V	14.91	−3.05	−0.41	9.99
105452..........	14	0.32	F2 III–IV	7.32	−2.26	1.09	12.34
111397..........	72	0.02	A1 V	13.50	−0.63	−10.01	2.38
111456..........	24	0.46	F5 V	13.47	0.51	−9.74	1.27
112185..........	20	−0.02	A0pCr	9.58	−0.56	−7.55	4.43
112394..........	25	0.70	G5 IV–V	...	...	...	...
115659..........	37	0.92	G8 IIIa	9.22	5.11	−11.23	5.72
116656..........	21	0.02	A1 VpSrSi	12.47	3.01	−5.22	4.20
116657..........	21	0.13	A1m	12.73	0.52	−8.13	1.48
118022..........	47	0.03	A1pSrCrEu	7.95	1.22	−16.13	8.75
124674..........	28	0.39	F1 V	8.02	−7.45	−18.72	14.14
124675..........	28	0.20	A8 IV	8.02	−7.45	−18.72	14.14
124752..........	23	0.81	K0.5 V	13.94	3.53	−9.26	2.14
124953..........	50	0.26	A8 III	13.39	1.04	−0.81	8.30
125451..........	46	0.38	F5 IV	20.66	8.88	−13.10	11.23
131156..........	6.4	0.76	G8 V	5.57	0.96	0.41	12.18
137107..........	16	0.58	G0 V	13.35	−5.65	−13.11	8.24
137108..........	16	0.58	G3 V	13.35	−5.65	−13.11	8.24
138481..........	50	1.59	K5 III	−2.49	−7.99	−6.85	18.46
139006..........	22	−0.02	A0 V	15.03	2.44	−7.29	2.76
148112..........	24	0.00	B9pCr	1.92	−3.45	−9.43	12.29
159561..........	15	0.15	A5 III	20.63	0.71	−8.38	7.56
197461..........	56	0.32	A7 IIIp	15.66	0.91	−3.75	5.94
204139..........	160	1.44	K5 III	35.71	−11.00	−5.89	26.02
209625..........	70	0.23	A5 m	15.39	0.36	−21.31	12.47
210459..........	96	0.46	F5 III	1.42	1.27	−2.36	13.53

single and appears to be presently the best case for X-ray emission from single A stars. For β Eri we were able to determine an X-ray temperature (see § II*e*) which is typical of those found in F and G type giant stars; hence the X-ray emission may actually arise from the A star but further data are definitely needed to confirm this suggestion.

c) X-Ray Luminosity and Kinematics

In Figure 3 we plot the Galactic velocity components V, W as a function of U for those sample stars with available proper motion and radial velocity information. The U, V, and W velocity components were recomputed (see Johnson and Soderblom 1987), using data from various sources in an attempt to use the most up to date measurements available in the SIMBAD data base, and a compilation of the resulting U, V, and W components is given in Table 2. Figure 3 shows a rather large dispersion of the components in velocity space; even the space velocity of the nucleus is not quite clear, taken as $U_{nuc} = 13.9$ km s^{-1}, $V_{nuc} = 1.5$ km s^{-1}, and $W_{nuc} = -9.4$ km s^{-1} by Eggen (1983) and $U_{nuc} = 12.4$ km s^{-1}, $V_{nuc} = 1.6$

TABLE 3

DETECTION AND UPPER LIMIT SUMMARY FOR THE URSA MAJOR CLUSTER/STREAM

Spectral Type	Luminosity Class	Detections	Upper Limits
B	All	0	1
A	IV + V	1	14
	III	2	2
	All	3	17
F	IV + V	4	1
	III	1	1
	All	5	2
G	IV + V	5	1
	III	4	0
	All	9	1
K	IV + V	1	1
	III	0	2
	All	1	3

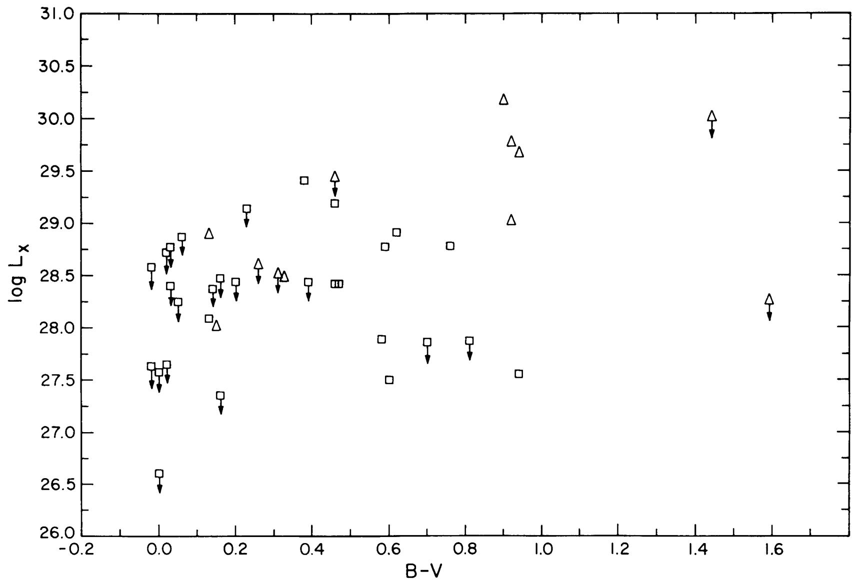

FIG. 1.—X-ray luminosity vs. $B-V$ for our sample stars; main-sequence stars and giants are denoted by squares and triangles, respectively. Upper limits are distinguished by downward-pointing arrows.

km s^{-1}, and $W_{\rm nuc} = -8.8$ km s^{-1} by Palous and Hauck (1986). The reason for the rather large velocity dispersion is presumably field star contamination of our sample.

Walter *et al.* (1984) and Soderblom and Clements (1987) have used activity as measured through X-ray fluxes and Ca II H and K fluxes, respectively, as an additional discriminator to separate true cluster members from field star interlopers; a somewhat similar approach, based on X-ray luminosities, has been adopted by Micela *et al.* (1988) for assessing membership of ≈10 doubtful Hyades members. Soderblom and Clements (1987) argue that up to 40% of their sample might be field star–contaminated, whereas Walter *et al.* (1984) claim four of 11 presumed group members to be field stars. This assignment of cluster membership according to activity is *a posteriori* and is based on an *a priori* notion of the evolution of stellar activity as a function of age. Because we wish to test whether the X-ray luminosity level of the Ursa Major members is consistent with the decrease of X-ray luminosity with increasing stellar age, as previously found in other coeval stellar samples, here we have chosen not to use activity as a selection criterion.

As a working hypothesis, we assume that the presumed Ursa Major group members consist of a population component (in velocity space) of true group members concentrated toward the nucleus with the space motion $\mathbf{V}_{\rm nuc}$ and a population component of false members more or less homogeneously distributed in the region of velocity space considered. If we then consider all stars with velocities inside a sphere of radius r in velocity space centered on the nucleus's velocity vector, the

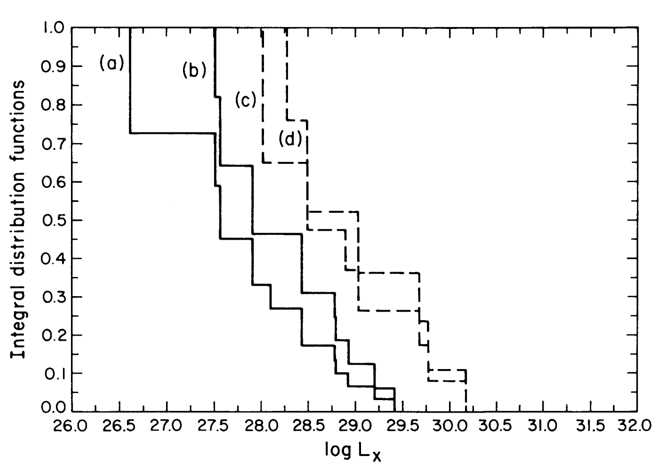

FIG. 2.—Kaplan-Meier estimates of the cumulative X-ray luminosity distribution functions for (*a*) all main-sequence stars in our sample, (*b*) late-type ($0.3 < B-V$) main-sequence stars, (*c*) all giants in our sample, and (*d*) late-type ($0.3 < B-V$) giant stars.

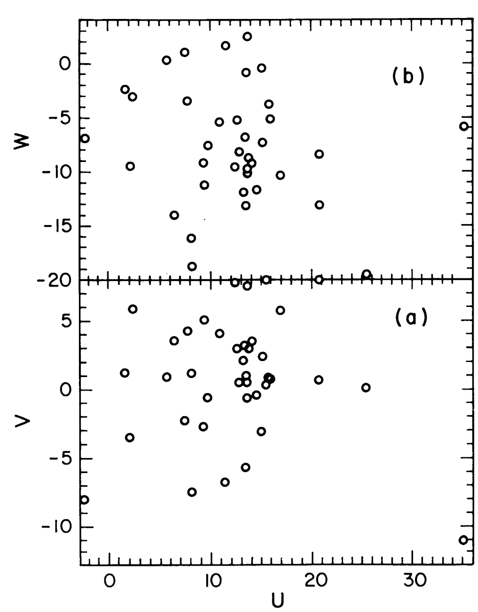

FIG. 3.—Galactic velocity components V (panel *a*) and W (panel *b*) plotted as functions of U for sample stars.

TABLE 4A

SINGLE-TEMPERATURE FITS

HD (1)	Sequence (2)	log T (3)	1 σ (4)	χ_{red}^2 (5)	EM (10^{49} cm^{-3} pc^{-2}) (6)	log L_X (ergs s^{-1}) (7)
5516..........	4940	7.02	0.10	0.71	1.66	29.74
33111..........	5471	7.12	0.08	1.81	1.17	29.03
85444..........	7607	6.98	0.10	0.68	1.20	29.88
105452..........	5538	6.43	0.03	0.99	0.66	28.81
111456..........	7913	6.65	0.06	1.20	1.28	29.30
115659..........	7682	6.57	0.23	1.72	0.35	29.12
125451..........	9705	6.61	0.11	0.68	0.57	29.51

TABLE 4B

TWO-TEMPERATURE FITS

			1 σ RANGE			1 σ RANGE						
HD (1)	SEQUENCE (2)	log T_1 (3)	Lower (4)	Upper (5)	log T_2 (6)	Lower (7)	Upper (8)	χ_{red}^2 (9)	EM$_1$ (10^{49} cm^{-3} pc^{-2}) (10)	EM$_2$ (10^{49} cm^{-3} pc^{-2}) (11)	log L_{X_1} (ergs s^{-1}) (12)	log L_{X_2} (ergs s^{-1}) (13)
39587..........	4347	5.80	5.00	6.36	7.00	6.90	7.10	0.15	2.46	2.45	27.67	28.83
72905..........	6964	6.45	6.36	6.51	7.05	6.90	7.27	1.50	1.24	0.87	28.86	28.65
131156..........	10418	6.45	6.39	6.46	7.30	7.13	7.52	1.20	4.36	5.83	28.72	28.57

percentage of true cluster members among stars inside that sphere should be larger than that for stars outside that sphere. If younger stars are more X-ray luminous than older field stars, the X-ray luminosity distribution functions for the two groups of stars should be different. Since in both subsamples stars with detections and upper limits are found, we are again facing a problem with censored observations to which special analysis methods must be applied (Schmitt 1985; Feigelson and Nelson 1985). Taking $r = 10$ km s^{-1} (this value exactly halves the available sample) and considering only stars with $B-V > 0.3$, we are unable to find any systematic differences between the two groups of sample stars. Test statistics and corresponding probabilities (that the two distributions are derived from the same parent distribution), respectively, have been computed as follows for the indicated techniques: Gehan, 0.19 and 0.85; log-rank, 0.64 and 0.52; Cox-Mantel, 0.64 and 0.52; and generalized Wilcoxon, 0.30 and 0.76 (see Schmitt 1985 and Feigelson and Nelson 1985 for a detailed description of the test procedures).

However, this result is not surprising because the sample (20 stars) considered in the above analysis is strongly affected by the presence of nine giants for which there is presently no evidence for the dependence of X-ray luminosity upon age. Moreover, five of the 12 main-sequence stars in the sample have color index in the range $0.3 < B-V < 0.5$, and in this range there is not conclusive evidence of an age dependence of X-ray luminosity (Micela *et al.* 1988, 1990). The present sample of main-sequence stars with $B-V \gtrsim 0.5$, for which the age dependence has been proven (Micela *et al.* 1988, 1990), is too small to permit a detailed statistical analysis. Hence, we conclude that the relatively small data sample must be enlarged before drawing conclusions regarding the potential departure of UMa–group stars from the general trend of decaying X-ray luminosity with increasing stellar age (Vaiana 1983; Micela *et al.* 1988, 1990; Feigelson and Kriss 1989; Walter *et al.* 1988).

d) X-Ray Temperatures

For those sample stars with sufficient X-ray counts, we performed spectral analyses of the IPC pulse height data as described in Schmitt *et al.* (1987, 1990); the one- and two-temperature fits resulting from these analyses are presented in Tables 4A and 4B. In Table 4A, we give for each star its HD number and sequence number in columns (1) and (2), the resulting best-fit single temperature with its error in columns (3) and (4), the reduced χ^2 of the fit in column (5), and the emission measure (in units of 10^{49} cm^{-3} pc^{-2}) of the best-fit spectrum and the X-ray luminosity with the distance as given in Table 1) in columns (6) and (7).

For three stars, HD 39587 = χ^1 Ori, HD 72905 = π^1 UMa, and HD 131156 = ξ Boo, the values of the reduced χ^2 for the attempted one temperature fits were unacceptable (i.e., above 2.5; see the extensive discussion in Schmitt *et al.* 1990), but the two-component fits were acceptable.[2] The parameters of these fits are given in Table 4B where we give HD and sequence number in columns (1) and (2), low-temperature component with lower and upper temperature bounds (cols. [3]–[5]), the high-temperature component with lower and upper temperature bound (cols. [6]–[8]), the reduced χ^2 of the fit (col. [9]), the derived emission measures of the two spectral components (cols. [10] and [11]; same units as Table 4A) and the inferred component X-ray luminosities (cols. [12] and [13]) based on the distances given in Table 1.

The determination of X-ray temperatures from low spectral resolution IPC data is not a plasma diagnostic in the strict sense, but is a rather model-dependent process with severe limitations; some of these have been noted by Schmitt *et al.* (1987) and Schmitt (1988) and will be discussed in more detail

[2] For one other star, μ Vel = HD 93497, we could obtain no satisfactory fit with either one- or two-component descriptions. This G giant, binary star might warrant further spectral observations.

by Schmitt *et al.* (1990). For present purposes one should consider the X-ray temperatures quoted in Table 4 as effective temperatures which depend on the actual coronal temperature stratification and the spectral characteristics of the instrument used. In particular we emphasize that we do not necessarily consider the occurrence of different spectral components as manifestations of physically distinct stellar active regions, although this could in principle be the case.

We observe that two out of the three two-component fits required (for π^1 UMa and ξ Boo) are such that the luminosity in the low-temperature component exceeds that in the high-temperature component. Such a luminosity distribution is in contrast to that typically found in nearby dwarfs (Schmitt *et al.* 1990) and defies explanation with the "standard" constant pressure and constant cross section loop model. This suggests either the presence of at least two different populations of loops on these stars or the presence of loops in which the pressure is not constant.

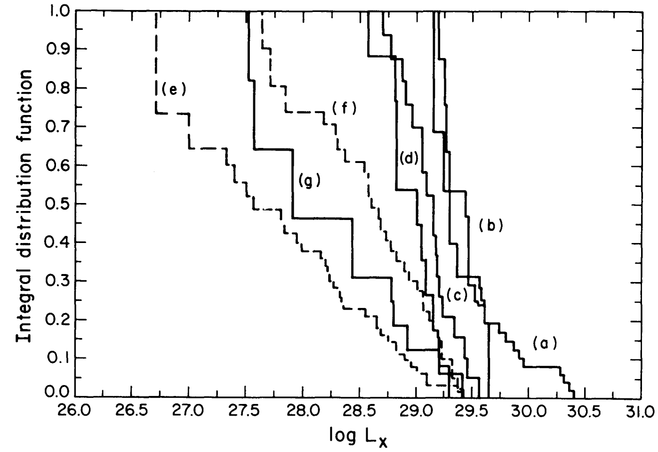

FIG. 4.—Kaplan-Meier estimate of the cumulative X-ray luminosity distribution function for the Pleiades G and F stars (curves *a* and *b*), for the Hyades G and F stars (curves *c* and *d*), for the field G and F stars (curves *e* and *f*), and for the Ursa Major main-sequence G and F stars combined (curve *g*).

IV. DISCUSSION AND CONCLUSIONS

We have carried out a complete X-ray survey of the Ursa Major cluster (nucleus and stream) utilizing all presently available X-ray data. The *Einstein Observatory* data have been reduced with the final Rev-1 processing software, and X-ray temperatures have been determined and reported whenever possible.

With 42 late-type Ursa Major candidate stars surveyed, 18 were detected thereby doubling the number of previously detected Ursa Major candidate stars. Our survey confirms the deficiency of X-ray emission from A type stars; however, one apparently single A type giant—β Eri—was found to exhibit high levels of X-ray emission. Among F and G stars, the detection rate is very high. The severe incompleteness of the optical candidate stars at fainter absolute magnitudes prevents any consideration of their detection rate.

We have not found any correlation between X-ray luminosity L_X and rotational velocity $v \sin(i)$. However, the range of sampled rotational velocity values is rather small, and therefore this negative finding does not necessarily mean that a rotation-activity relationship is absent for the Ursa Major cluster stars.

A major problem affecting all Ursa Major cluster studies is field star contamination. We have been unable to confirm previous suggestions that X-ray luminosity can be used as a sensitive membership criterion. Unfortunately this conclusion rests on a relatively small number of sample stars, and other interpretations are also possible; for example, it may be that field star contamination is so large that both our test samples are almost equally affected.

If field star contamination is not a serious problem, the relationship between X-ray luminosity and age becomes questionable in the following sense: Micela *et al.* (1988) have carried out a comprehensive X-ray survey of the Hyades cluster and derived X-ray luminosity distribution functions as well as mean X-ray luminosities for the Hyades F stars ($\log L_X = 28.99$), the Hyades G stars ($\log L_X = 29.16$), and the Hyades K stars ($\log L_X = 28.62$). Our smaller data sample does not allow a breakdown into so many subgroups, but for main-sequence stars in the color range redder than $B - V = 0.5$, we find the value $\log L_X = 28.2 \pm 0.17$, substantially different from those found in the Hyades cluster. Even when all stars redder than $B - V = 0.3$ are considered, we find the mean Ursa Major X-ray luminosity below that of the Hyades.

This discrepancy becomes obvious upon examination of the X-ray luminosity distribution functions for the Pleiades, Hyades, the Ursa Major group, and field stars. In Figure 4 we show the cumulative distribution functions for the Pleiades G and F stars (curves *a* and *b*), the Hyades G and F stars (curves *c* and *d*), the G and F stars in the field (curves *e* and *f*), and the 12 Ursa major main-sequence F and G stars (curve *g*). We note that the Ursa Major distribution function more closely resembles that of the field stars than it does that of the Hyades; from Figure 4 it is clear that the mean X-ray luminosities for Ursa Major and for the Hyades are quite discrepant. This result seems to be at odds with previous findings of a decrease of X-ray luminosity level with stellar age in late-type main-sequence stars (Vaiana 1983; Micela *et al.* 1985, 1988, 1990; Caillault and Helfand 1985; Feigelson and Kriss 1989; Walter *et al.* 1988). Since the Hyades cluster is certainly not significantly younger than the Ursa Major group, the large discrepancy in the X-ray luminosity distribution function is quite surprising. The discrepancy could be naturally explained if the Ursa Major sample suffers substantial field star contamination. Indeed, Figure 4 indicates that if this is the case, the contamination level is substantial. While available data seem to indicate that the X-ray luminosity of the late-type main-sequence Ursa Major stars is lower than that of the Hyades stars, this indication rests on a small number of stars, seven in all, for which is very difficult to evaluate field star contamination. With the present data it remains questionable whether the Ursa Major group X-ray luminosity and age are consistent with the activity-age relationship previously shown to hold for the Hyades and Pleiades clusters (cf. Micela *et al.* 1988, 1990) and, as a corollary of that, whether X-ray luminosity can be used to discriminate between field stars and Ursa Major group members.

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