THE *EINSTEIN OBSERVATORY* SURVEY OF STARS IN THE HYADES CLUSTER REGION

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Received 1987 March 4; accepted 1987 July 29

ABSTRACT

We report the results of an extensive X-ray investigation of the Hyades region and improve upon previous studies by using refined X-ray source detection algorithms and the complete set of *Einstein Observatory* imaging proportional counter exposures covering the Hyades cluster region (a total of 63 1° × 1° images). Using a somewhat more extensive and complete compilation of optical candidates, we have detected 66 out of 121 Hyades members falling in the combined fields of view, compared with a detection rate of 48 out of 85 Hyades members in the original *Einstein* survey of the central 5° of the cluster. We have also computed 3 σ upper limits for all the nondetected Hyades members and have derived maximum-likelihood X-ray luminosity functions for the Hyades stars in selected spectral type ranges, using both detections and upper limits. A comparison of the X-ray luminosity functions of the Hyades stars with analogous functions derived for other groups of coeval stars suggests that the dependence of the level of X-ray emission on stellar age is itself a function of stellar color. We also compare the number of X-ray sources identified with field stars with the expected number predicted on the basis of the Bahcall/Soneira galaxy model and the known X-ray luminosity functions for field stars in given spectral type range and discuss a discrepancy which emerges for the dG stars.

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

I. INTRODUCTION

The Hyades cluster region, which has been extensively studied in the optical waveband, provides one of the best stellar samples available for studying stellar activity. In this paper, we take advantage of the ready availability of optical data for the cluster members and examine the X-ray properties of all stars in the Hyades region of the sky using data obtained with the *Einstein Observatory*. This work represents a refinement of previous work on the Hyades cluster (Stern *et al.* 1981), and when taken together with recent studies of the Pleiades cluster (Caillault and Helfand 1985; Micela *et al.* 1985), constitutes a study of the temporal evolution of stellar activity as seen at X-ray wavelengths.

Whereas the previous *Einstein* survey of this cluster (Stern *et al.* 1981) was limited to the central region of the cluster and did not have available all imaging proportional counter (IPC) exposures containing Hyades members, the present survey makes use of all IPC exposures containing at least one Hyades star. Moreover, while the Stern *et al.* survey was based on the original version of the *Einstein* data reduction software system, the final data reduction analysis system used here allows a more sensitive detection of faint sources and permits us to compute upper bounds for all of the nondetected cluster members falling in the combined field of view. (Knowledge of the upper bounds is essential for a correct statistical analysis of

the survey results; cf. Avni *et al.* 1980; Schmitt 1985.) The present study thus represents the most complete and definitive Hyades survey which can be based on the *Einstein Observatory* data and will therefore provide a useful comparison for future X-ray observations.

Our paper is organized as follows. We first describe the selection procedure used to compile the optical catalog on which this survey is based (§ II). Our data selection and data analysis methods are presented in § III as well as in the Appendices, where we discuss extensively the determination of source fluxes (Appendix A) and the treatment of partially obscured sources (Appendix B). Our results are presented and discussed in § IV, for X-ray sources identified with field stars, and in § V, for the Hyades members according to spectral type. We summarize our results in § VI.

II. CHARACTERISTICS OF THE OPTICAL CATALOG

We have constructed an optical catalog of 323 certain or probable Hyades members, using the published optical catalogs available 1985 June with sufficiently accurate positions (fraction of arcmin) and information on cluster membership. The nucleus of our compilation comprises the van Bueren catalog (van Bueren 1952; Pels, Oort, and Pels-Kluvyer 1975), covering the entire region of the Hyades cluster (≈20° × 20°) with completeness down to 9th mag; for stars fainter than 9th mag in the central region of the Hyades (≈4° × 4°), we retained all those stars assigned a membership probability greater than 20% by Hanson (1975) or van Altena (1969), preferring the Hanson evaluation when available. We also
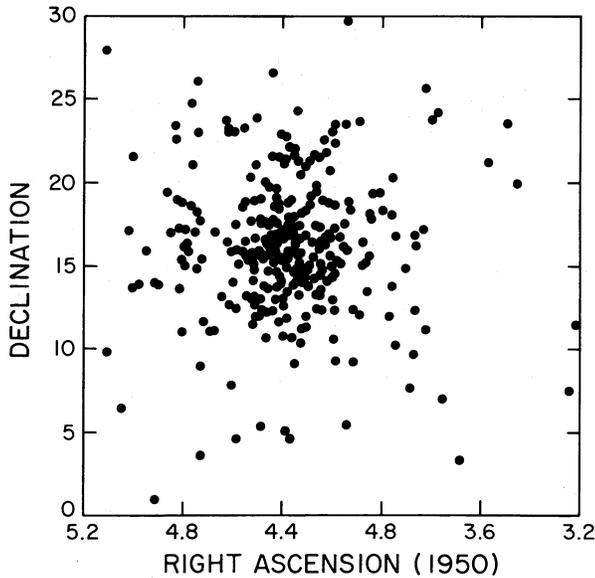
Fig. 1.—Spatial distribution of the Hyades members in our total optical catalog compilation (including the Pels, van Bueren, van Altena, and Giclas catalogs).

included the Leiden stars (Pels *et al.*) accepted by Hanson (1975) on the basis of proper motion criteria, or by Johnson, Mitchell, and Iriarte (1962) and Upgren and collaborators (Upgren 1974; Upgren and Weiss 1977; Upgren, Weiss, and DeLuca 1979; Weiss, DeLuca, and Upgren 1979; Weiss and Upgren 1982) on the basis of photometric criteria. Furthermore, we added stars to the final list from Region 7 of the Giclas, Burnham, and Thomas (1962) survey which are considered to be certain or probable cluster members both on the basis of proper motion criteria (Giclas *et al.*) and on photometric criteria (Upgren 1974; Upgren and Weiss 1977, Upgren
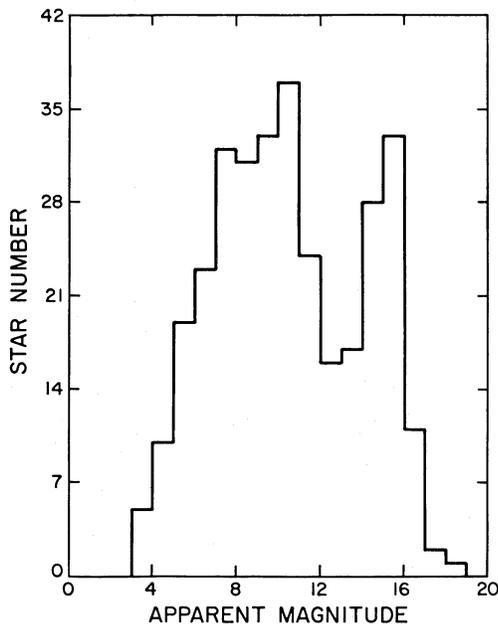
et al., Weiss *et al.*, Weiss and Upgren 1982). Finally, we added a handful of stars from various other catalogs: three stars found in the Luyten survey (Luyten, Hill, and Morris 1981), one Hertzsprung star in the Pleiades region of the sky, one MCL star, and one BD star, all quoted as certain members (see references at the end of Table 2).

The spatial distribution of cluster members is shown in Figures 1; the corresponding magnitude distribution is shown in Figure 2.

Since the catalogs on which we based our compilation differ considerably in sky coverages and selection criteria, our optical catalog cannot be considered complete. However, over the entire Hyades region, our catalog can be considered complete to 9th mag (i.e., early K at the Hyades distance) because of the completeness of the van Bueren catalog. We note in passing that the van Altena catalog includes stars up to 17th mag in the central region of the cluster.

III. DATA SELECTION AND DATA ANALYSIS

We have analyzed 63 *Einstein Observatory* IPC images containing at least one Hyades member of our cluster catalog. The list of these images with some relevant information is given in Table 1. The sky coverage of our survey is shown in Figure 3*a*, and the positions of the 121 Hyades members observed in the combined fields of view (whether detected or not) are shown in Figure 3*b*. About half of these stars have been observed more than once (in particular, all stars in the central Hyades region have been observed more than twice). The relevant optical data for the 121 certain Hyades members present in our survey are summarized in Table 2A; the magnitude distributions of all Hyades stars in our survey (*solid line*) and of the certain Hyades stars detected as X-ray sources (*dashed line*; cf. § V) are displayed in Figure 3*c*. We list in Table 2B relevant optical data for 10 stars (brighter than 9th mag) whose Hyades membership has been rejected by Hanson (1975) (cf. § IV).

a) Detection Method

All IPC images have been analyzed with the final IPC processing (REV-1) software. The standard source detection algorithm takes into account the spatial and temporal gain variations in the IPC field of view and analyzes each image with two different methods of detection: the *Local* detect and the *Map* detect algorithms. Local detect searches for fluctuations with respect to the local background, while Map detect searches for fluctuations with respect to background reference maps (Harnden *et al.* 1984). The latter method is more sensitive than the first (particularly in crowded fields), but finds more spurious sources in regions with weak diffuse emission.

In the REV-1 system, the two methods are applied separately in three (not entirely independent) energy bands: soft (0.2–0.8 keV), hard (0.8–3.5 keV), and broad (0.2–3.5 keV); the detection thresholds (expressed in terms of approximate Gaussian "sigmas") are chosen in such a way that, on average, no more than 0.3 spurious detections for each band and for each method will be found in each field (i.e., ~1.8 spurious detections per field). The detection threshold in the present survey was never less than 2.5 σ.

For the purpose of the Hyades survey we have applied acceptance criteria more restrictive than those applied by the REV-1 system. We retain only X-ray detections obtained in the broad band, either by the Local detect or the Map detect algorithm; this choice gives our survey a high level of internal

Fig. 2.—Magnitude distribution of our total optical catalog, including data from the Pels, van Bueren, van Altena, and Giclas catalogs.

TABLE 1

CHARACTERISTICS OF OBSERVATIONS

Sequence Number	R.A. (1950)	Decl.	Start Date Stop Date	Live Time (ksec)	Sequence Number	R.A. (1950)	Decl.	Start Date Stop Date	Live Time (ksec)
I303	4^{h}10^{m}36^s	10°22'00"	1979 Mar 6 / 1979 Mar 6	3.5	I3668[a]	4 20 00	17 55 12	1979 Sep 9 / 1980 Feb 20	3.2
I350	4 30 30	5 15 00	1979 Mar 8 / 1979 Mar 9	14.2	I3816	4 18 04	19 25 19	1980 Feb 15 / 1980 Feb 15	2.7
I351	4 30 30	5 15 00	1979 Aug 15 / 1979 Aug 30	30.3	I3818	4 26 04	26 16 52	1980 Feb 15 / 1980 Feb 15	5.6
I867	4 29 24	17 38 00	1981 Jan 31 / 1981 Jan 31	2.1	I3819	4 30 54	18 06 32	1980 Feb 15 / 1980 Feb 15	2.6
I1939	4 30 30	5 15 00	1979 Aug 15 / 1979 Aug 15	0.8	I3988	4 06 35	12 09 50	1980 Feb 10 / 1980 Feb 10	1.8
I2683	3 56 10	10 17 32	1980 Feb 10 / 1980 Feb 10	1.2	I4451	4 33 03	16 24 37	1980 Mar 2 / 1980 Mar 2	1.3
I3284	4 16 24	21 01 24	1979 Feb 28 / 1979 Feb 28	1.3	I4476	4 22 55	15 34 00	1979 Sep 10 / 1979 Sep 10	1.5
I3510	4 20 00	15 30 00	1979 Sep 10 / 1979 Sep 10	2.0	I4516	4 31 52	24 22 51	1980 Mar 4 / 1980 Mar 4	2.0
I3511	4 28 43	15 54 00	1979 Sep 10 / 1979 Sep 10	2.1	I6311[a]	3 56 11	10 17 32	1980 Mar 4 / 1981 Feb 16	6.4
I3512[a]	4 25 48	16 18 36	1979 Sep 11 / 1980 Mar 2	2.6	I6735	4 58 56	13 51 49	1980 Feb 22 / 1980 Feb 22	2.5
I3513	4 25 48	15 30 29	1979 Sep 9 / 1979 Sep 9	1.9	I7247	4 29 00	18 00 00	1981 Jan 31 / 1981 Jan 31	10.6
I3514	4 31 36	16 18 36	1979 Sep 11 / 1979 Sep 11	1.4	I7408	3 50 20	23 36 00	1981 Feb 10 / 1981 Feb 10	2.4
I3515	4 31 36	15 30 00	1979 Sep 9 / 1979 Sep 9	2.0	I7433	4 10 50	10 05 12	1980 Feb 9 / 1980 Feb 9	1.2
I3516	4 22 55	16 42 36	1980 Feb 20 / 1980 Feb 20	1.7	I7434	4 19 04	19 25 05	1981 Feb 10 / 1981 Feb 10	1.9
I3517[a]	4 20 31	15 54 00	1979 Mar 7 / 1980 Feb 20	2.4	I7512	5 06 43	10 08 11	1980 Aug 26 / 1980 Aug 26	1.7
I3518	4 22 55	15 06 00	1979 Sep 9 / 1979 Sep 9	2.0	I7630	4 46 21	11 16 45	1981 Mar 8 / 1981 Mar 8	3.6
I3519	4 20 00	17 06 36	1979 Mar 7 / 1979 Mar 7	1.9	I8978	4 09 45	22 57 31	1981 Jan 31 / 1981 Feb 1	5.0
I3520	4 20 00	16 18 36	1979 Mar 7 / 1979 Mar 7	1.2	I9000	4 15 29	17 08 05	1980 Sep 19 / 1980 Sep 19	9.1
I3521[a]	4 20 00	14 41 24	1979 Sep 9 / 1980 Feb 19	2.6	I9001	4 23 48	16 38 08	1980 Sep 18 / 1980 Sep 19	5.1
I3522[a]	4 20 00	13 53 24	1979 Sep 9 / 1980 Feb 10	3.4	I9002	4 19 54	14 56 25	1981 Jan 30 / 1981 Jan 30	8.4
I3523[a]	4 22 55	14 17 24	1979 Sep 9 / 1980 Feb 19	3.3	I9003	4 21 22	14 38 38	1981 Jan 30 / 1981 Jan 30	9.4
I3524[a]	4 25 48	14 41 24	1979 Sep 9 / 1980 Feb 20	2.7	I9004	4 23 30	15 30 23	1980 Sep 19 / 1980 Sep 19	10.8
I3525[a]	4 28 43	15 06 00	1979 Sep 9 / 1980 Feb 20	2.4	I9005	4 25 43	15 51 10	1981 Jan 30 / 1981 Jan 31	4.7
I3526[a]	4 28 43	16 42 36	1979 Sep 11 / 1980 Mar 2	1.9	I9006	4 27 55	16 02 30	1981 Jan 31 / 1981 Jan 31	6.1
I3527	4 25 48	17 06 36	1980 Mar 2 / 1980 Mar 2	2.0	I9917	3 46 30	24 30 00	1981 Feb 8 / 1981 Feb 8	6.1
I3528	4 22 55	17 31 12	1980 Mar 2 / 1980 Mar 2	4.0	I9919	3 46 30	23 30 00	1981 Feb 7 / 1981 Feb 8	5.8
I3662	4 31 36	14 41 24	1980 Feb 20 / 1980 Feb 20	3.2	I10069	4 31 54	24 23 10	1981 Feb 7 / 1981 Feb 7	9.5
I3663	4 17 05	15 06 00	1980 Feb 10 / 1980 Feb 10	2.7	I10075	4 28 07	20 31 09	1981 Feb 2 / 1981 Feb 2	2.8
I3664	4 17 05	15 54 00	1980 Feb 10 / 1980 Feb 10	2.4	I10410	4 20 37	14 49 10	1981 Feb 10 / 1981 Feb 10	2.7
I3665	4 17 05	14 17 24	1980 Feb 10 / 1980 Feb 10	2.7	I10412	4 23 42	16 35 07	1981 Feb 10 / 1981 Feb 10	1.7
I3666	4 17 05	16 42 36	1980 Feb 10 / 1980 Feb 10	2.9	I10434	3 58 48	10 16 00	1981 Feb 16 / 1981 Feb 16	2.0
I3667[a]	4 17 05	17 31 12	1980 Feb 20 / 1980 Mar 2	6.6					

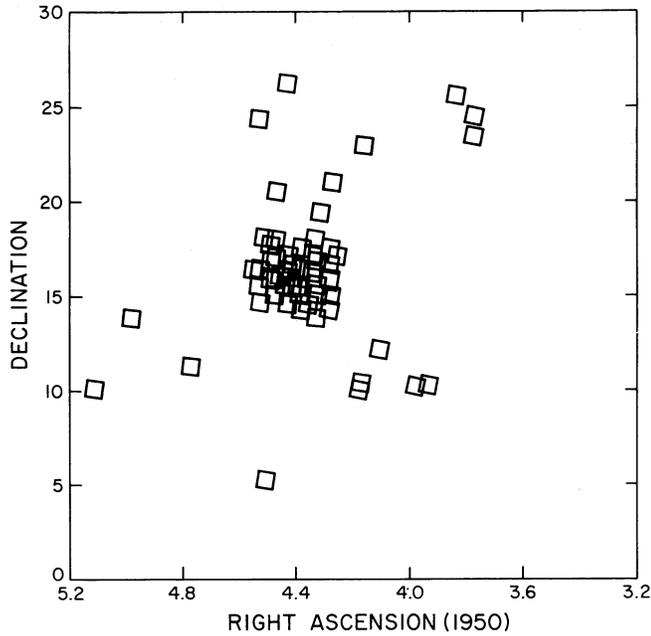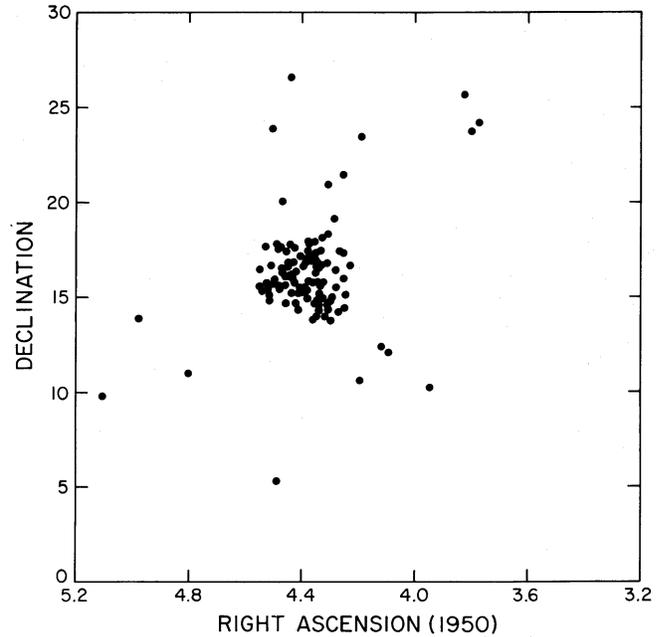[a] Sequence contains merged data acquired at epochs spanning months.

FIG. 3a

FIG. 3b

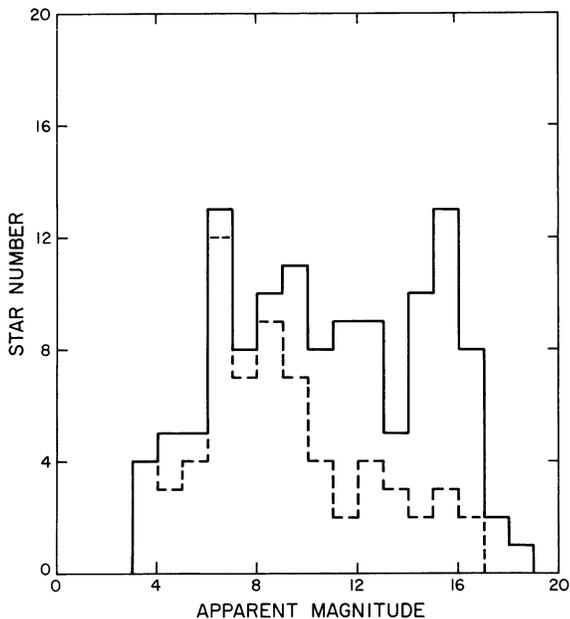
FIG. 3c

FIG. 3.—(a) Sky coverage of the present Hyades survey. Each square of 1° × 1° represents one or more IPC fields. Note the crowding of the fields in the central region of the cluster. (b) Spatial distribution of the Hyades stars observed in the present X-ray survey. (c) Magnitude distribution of the Hyades stars in the present survey (*solid line*) and magnitude distribution of the Hyades stars detected as X-ray sources (*dashed line*).

consistency in the detection criteria used and reduces the statistically expected number of spurious detections by a factor of 3, i.e., from 114 to 38; hence our choice is also conservative. Moreover, we note that of 65 would-be detections obtained in the soft band only, or in the hard band only, and therefore discarded by our criteria, only two could be identified with Hyades cluster members; hence our choice is not inefficient.

b) Identifications of Hyades Sources

The REV-1 system automatically proposes a tentative identification for each X-ray detection whose position lies within a 3′ radius of a cataloged celestial object; this process is based on the *Einstein* master catalog, a collection of 60 distinct catalogs (Harris and Irwin 1984) that includes the catalog of the Hyades built for this specific survey. Because some of the exposures used in the present survey are pointed in the Taurus-Auriga region, for which the master catalog has few entries, we have searched, *a posteriori*, the Orion population catalog of Herbig and Rao (1972) for optical counterparts of detected X-ray sources in this region.

We have adopted a more stringent identification criterion for the present survey, namely that the optical object lie within 2′ of the X-ray source location. Only one of the X-ray sources identified with a Hyades member is more than 2′ from the star optical position; in this single case, we note that the X-ray source is near the edge (distance from the IPC center is 39′.2), where the acceptance criterion should be relaxed due to reduced instrumental accuracy in source position determination.

As can be seen from Table 3, we identify 116 X-ray detections with 66 distinct Hyades stars. More specifically, we have detected six of nine dA stars, 16 of 18 dF stars,[3] 13 of 15 dG stars,[4] 16 of 30 dK stars, 14 of 46 dM stars,[5] all three gK stars present in the total field of view, and one[6] out of three white dwarfs of spectral type A.

In addition, we have identified 72 X-ray sources with cataloged field objects: 61, with stars, and 11, with nonstellar

[3] Two of the X-ray sources have optical counterparts which are themselves members of optically resolved binary systems containing an F star with a G companion. These detections have been counted twice, both in the F star and the G star samples.
[4] See note 3.
[5] The white dwarf has a possible M companion which has been counted in the sample of M stars. The X-ray emission is very likely due to the M star.
[6] See note 5.

TABLE 2A

HYADES STARS IN OUR SURVEY

Name	R.A. (1950)	Decl. (1950)	m_v	$B-V$	Ref.	Sp.	Ref.	V	Ref.	Notes
Hz 2411/MLC 20/						M3	6			
LP 357-4	$3^h46^m42^s$	24°09'54"	14.21	1.62	1	M4e	7			Susp. Bin.
VB 170/L6/DM +23 571/J211	3 48 04	23 45 18	10.23	1.16	1	K5	*			
L7	3 49 40	25 39 24	11.15	1.30	1	K7	*			
VB 8/HD 25102/										
HR 1233/DM +9 524	3 56 56	10 11 23	6.37	0.42	2	F5	8	50	15	
L14/J233/GH 7-105	4 05 40	12 03 36	11.28	1.33	1	K8	*			
H14	4 07 14	12 20 18	15.63	1.55	3	M3	*			
VB 15/DM +23 649	4 11 32	23 27 03	8.09	0.66	2	G3 V	9	7 8	{18 {19	
VB 19/HD 26784/										
DM +10 551	4 11 49	10 34 35	7.14	0.51	2	F5	8	<12	15	
VA 95	4 13 54	16 38 58	17.07	2.05	4	M	*			
VA 118/GH 7-154	4 15 01	15 06 22	15.55		1	M3	6			
VA 122/GH 7-156	4 15 06	14 25 31	15.00	1.63	1	M5	*			
VA 127	4 15 16	17 17 44	16.19		1					
VA 131/LP 414-159	4 15 21	15 58 39	16.19		1					
VB 24/HR 1331/HD 27176/										51 Tau
DM +21 618	4 15 25	21 27 32	5.65	0.28	2	F0 V	10	125	12	SB3
VA 135/L30/J253/GH 7-160/										
DM +17 704	4 15 29	17 18 05	10.0	1.10	1	K	11			
VB 27/VA 156/HD 27282/										
DM +17 707	4 16 15	17 24 19	8.46	0.72	2	G8 V	9	5	19	Var
VA 162/HoB 29/GH 7-165/VR 1	4 16 31	14 11 49	12.79	1.49	5	M1	6			
VB 28/VA 175/HR 1346/										54 γ Tau
HD 27371/DM +15 612	4 16 57	15 30 30	3.66	0.99	2	K0 III	14	3.44 13	22 19	SB1
VB 29/VA 179/HD 27383/								10	{ 10	
DM +16 579	4 17 03	16 24 14	6.99	0.56	2	F7+G3	14	18, 8.5	{19, 18	Var? Bin.
VB 31/HD 27406/								12	{18	
DM +18 623	4 17 18	19 06 54	7.47	0.57	2	G0 V	9	10 12	{19 {19	
VB 33/HR 1356/HD 27459/										Var.
DM +14 682	4 17 46	14 58 38	5.26	0.22	2	A9 V	9	70	15	58 Tau SB1
VB 34/VA 201/HR 1358/										
HD 27483/DM +13 665	4 18 04	13 44 47	6.17	0.46	2	F6	9	12	15	SB2
VA 203/LP 475-9	4 18 06	14 44 31	16.70	1.62	5	M5	*			
VB 35/HD 27524/										
DM +20 740	4 18 34	20 55 23	6.80	0.44	2	F5 V	9	90	15	
VB 36/HD 27534/										
DM +18 629	4 18 38	18 18 02	6.80	0.44	2	F6 V	9	40	15	
VA 213	4 18 43	16 46 39	15.46		1	M3	6			
VB 37/VA 215/HD 27561/										
DM +14 687	4 18 45	14 17 33	6.61	0.41	2	F4	9	12	15	
VA 216	4 18 45	14 34 41	15.64	0.96	4	M2	6			
VB 38/VA 229/HR 1368/										Var. δ Scuti
HD 27628/DM +13 668	4 19 14	13 57 39	5.72	0.32	2	A3m	10	15	15	SB1 60 Tau
VA 241	4 19 41	15 44 28	15.36	1.84	4	M	*			
VA 242/L 41/GH 7-179/										
LP 415-27	4 19 45	18 09 13	13.01	1.51	1	M0.5	6			
VB 39/VA 248/HD 27685/										
DM +16 585	4 19 52	16 40 32	7.86	0.68	2	G5	13			Var?
VB 40/VA 249/HD 27691/						G0 V	9			
DM +14 690	4 19 54	14 56 25	6.99	0.56	2	F8 IV	14	8	15	SB(3)
VB 41/VA 256/HR 1373/										SB3
HD 27697/DM +17 712	4 20 03	17 25 37	3.77	0.98	2	K0 III	14	1.99	22	61 δ¹ Tau
VA 260/LP 415-367	4 20 11	15 06 46	16.71	1.66	5	M6	*			
VA 262/LP 415-35	4 20 21	15 35 52	15.85	1.77	5	M8	*			
VB 43/DM +19 708	4 20 27	16 32 37	9.40	0.91	1	K2 V	9			
VB 45/VA 272/HD 27749/										63 Tau
HR 1376/DM +16 586	4 20 32	16 39 45	5.64	0.30	2	A1m	10	<12	20	SB1
VA 275/GH 7-187/										
LP 475-37	4 20 34	14 18 47	14.94	1.59	1	M2–3	6			Susp. Bin.
VB 173/VA 276/L35/GH 7-185/										
J173/O217/VR 4/HoA 55/										
KA 91/RaA 17/DM +15 616	4 20 34	15 38 54	10.51	1.23	1	K5 V	15			
VB 46/VA 279/VR 5/O226										Var
HD 27771/DM +14 691	4 20 42	14 33 20	9.12	0.86	1	K1 V	9			Bin?
VA 282/GH 7-189	4 20 51	15 45 59	14.82	1.55	6	M2	6			
VA 288/GH 7-190/						M2–3	6			Flare
VR 6/HoA 78	4 21 00	14 48 26	13.34	1.55	1	M3e	7			Susp. Bin.

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Name	R.A. (1950)	Decl. (1950)	m_v	$B-V$	Ref.	Sp.	Ref.	V	Ref.	Notes
VA 292/EG 36/VR 7/GH 7-191/										
LP 415-46/HoA 82/RaB 28	4 21 04	16 14 23	14.22	−0.02	4	DA	16			
VA 294/L34/GH 7-193/										
VR 9/HoB 61/O251/J262	4 21 05	13 56 15	10.90	1.28	1	K5.5	17			
VA 297/VR 8/GH 7-194/										
GH 8-74/J260/RaB 30/HoA 89	4 21 07	16 36 66	12.55	1.49	2	M0	6			
VB 47/VA 301/HR 1380/										SB
HD 27819/DM +17 714	4 21 13	17 19 47	4.80	0.16	2	A7.5 V	9	35	20	64 δ^2 Tau
VB 49/H307/HD 27835/								8	19	
DM +16 589	4 21 21	16 15 54	8.24	0.59	2	G0	8			Bin?
VB 50/VA 308/HD 27836/								7 10 13	11 19 19	
DM +14 693	4 21 22	14 38 39	7.62	0.60	2	G1 V	9			Var
VB 174/VA 310/L39/GH7-196/										
GY 54/O271/KA 113/HoB 66/										
DM +17 715	4 21 23	17 53 21	9.98	1.04	1	K4 V	9			
VB 51/VA 315/HD 27848/										
DM +16 591	4 21 29	16 57 54	6.97	0.44	2	F6 V	9	30	15	
VA 321/GH7-198/										
LP 415-59	4 21 37	15 46 14	14.93	1.58	4	M2–3	6			
VA 326	4 21 42	13 48 53	16.62	1.87	5	dM5.5	5			
VA 329	4 21 47	15 47 46	15.35		1					
VA 334/VR 11/RaA 47/O300/							M0	6			
HoA 134/GH 7-200	4 21 57	15 45 41	11.64	1.41	4	M0e	7			
VB 175/VA 342/L36/GH 7-201/										
DM +16 593	4 22 07	16 52 18	10.28	1.03	1	K4 V	9			
VA 351/L42/GH 7-203/										Flare
LP 415-65	4 22 20	17 09 19	13.21	1.54	1	M2	6			Susp. Bin.
VB 56/VA 355/HR 1389/										68 δ^3 Tau
HD 27962/DM +17 719	4 22 36	17 48 55	4.30	0.05	2	A3 V	9	<30	12	SB3
VB 57/VA 360/HD 27991/								15	15	Bin. Var?
DM +15 621	4 22 46	15 49 43	6.46	0.49	2	F7 V	9	18	19	70 Tau
VB 176/HD 27990/										
DM +17 721	4 22 51	17 54 27	9.01	0.94	2	K2 V	9			
VA 362/LP 415-71	4 22 53	17 25 57	15.87	1.73	5	M7	*			
VA 366/GH 7-208/							M0	6			
RaB 73/HoA 213	4 22 58	15 24 33	12.30	1.45	4	M1	7			
VA 368	4 23 00	14 53 25	16.27	1.58	5	M4	*			
VA 382/O433/GH 7-218/										
LTT 11425/GH 8-39/KA 189/										
LP 415-414/HoA 320/RaA 117	4 23 11	17 00 32	15.59		1					
VA 383/O373/GH 7-212/										
LP 475-68/HoA 239/RaB 85	4 23 14	14 55 46	12.14	1.45	4	M2	7			
VB 59/VA 384/HD 28034/								<6 11 13	15 19 19	Var
DM +15 624	4 23 15	15 24 44	7.49	0.54	2	F8 V	9			Bin.
VB 141/VA 388/HD 28052/							A8 Vn	10			Var δ Scuti SB3
HR 1394/DM +15 625	4 23 30	15 30 23	4.48	0.25	2	F0 V	14	160	21	71 Tau
VB 63/VA 389/HD 28068/								7 6 10	18 11 19	Bin.
DM +16 598	4 23 32	16 44 30	8.06	0.63	2	G5 V	9			Var
VB 64/VA 400/HD 28099/								5 6 6	18 11 19	
DM +16 601	4 23 48	16 38 08	8.12	0.66	2	G6 V	9			Var
VA 410	4 24 11	15 16 18	16.13	1.69	4	M6	*			
VA 420/GH 7-221/							M1	6			
HoA 339	4 24 23	17 07 53	13.02	1.49	5	M1	7			
VA 444/VR 39/GH 7-223/										
O469/RaA 142/KA 205/HoA 363 .	4 24 41	15 15 18	11.07	0.81	4	K0 V	15			
VB 65/VA 446/HD 28205/								9 21 21	9 16 3	
DM +15 627	4 24 45	15 28 44	7.42	0.54	2	F8 V	15			Var?
VB 179/VA 459/L52/RaA 151/										
GH 7-225/O484/KA 212/										
HoA 389/GY 77/VR 13/J274/										
DM +14 699	4 24 57	14 18 27	9.48	0.93	1	K2	13			
VB 189/VA 475/L53/HoA 426/							K	6			
GH7-230/O514/VR 14/							M0	7			
GY 78/KA 215	4 25 19	16 21 41	11.11	1.35	1	K5 V	17			76 Tau

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Name	R.A. (1950)	Decl. (1950)	m_v	$B-V$	Ref.	Sp.	Ref.	V	Ref.	Notes
VB 68/VA 485/HR 1408/ HD 28294/DM +14 702 ...	4 25 33	14 37 53	5.90	0.32	2	F0 V	9	135	12	Bin?
VA 486/L68/GH 7-232 ...	4 25 35	17 35 12	12.16	1.48	1	M1	6			Susp. Bin.
VB 71/VA 489/HR 1411/ HD 28307/DM +15 631 ...	4 25 43	15 51 10	3.85	0.96	2	K0 III	14	2.4	22	77 θ^1 Tau SB1 4
VA 490/EG 37/O545/VR 16/ GH 7-233/LP 415-115/ HoA 465/RaB 169 ...	4 25 47	16 51 40	14.02	−0.09	4	DA	16			Var δ Scuti
VB 72/VA 491/HR 1412/ HD 28319/DM +15 632 ...	4 25 48	15 45 42	3.41	0.18	2	A7 IVn (9) A7 III (8)		130	12	78 θ^2 Tau SB1
VB 190/VA 500/L54/GH 7-234/ RaA 192/O556/VR 17/KA 229/ HoA 484/GY 84 ...	4 25 59	16 10 48	10.71	1.32	1	K8 V	17			Bin?
VA 502/VR 18/GH 7-235/O558/ HoA 489/MLC 46/RaA 194 ...	4 26 01	15 52 22	11.96	1.44	4	M0-1 (7) K7 Ve (17)				
VB 75/VA 511/HD 28363AB/ DM +15 633 ...	4 26 08	16 03 01	6.59	0.53	2	F7+G0	14	<30	12	SB1
VA 512/GH 7-236 ...	4 26 08	16 14 16	14.28	1.53	5	M1-2	6			
VA 529/VR 19/GH 7-238/ LP 475-97/LP 415-378/ HoA 521/RaB 186 ...	4 26 21	15 09 55	12.44	1.47	4	M0 (6) M1 (7)				
VB 76/HD 283704/ DM +26 722 ...	4 26 26	26 33 50	9.18	0.77	2	G8	13			
VB 78/VA 544/HD 28406 ...	4 26 36	17 45 18	6.92	0.45	2	F6 V	15	20 / 21	{9 / 11}	Bin.
VB 181/VA 548/L55/RaA 213/ GY 91/KA 238/HoA 542/VR 20/ O595/GH 7-241/HD 285805/ DM +15 634 ...	4 26 39	16 08 12	10.32	1.15	1	K5 V	17			
VA 559/GH 7-244/ HoA 576/RaB 212 ...	4 27 03	16 48 23	12.75	1.48	5	M0-1	7			
VB 180/VA 560/L56/GH 7-246/ O662/HoA 579/VR 21/KA 242/ GY 93/RaA 222/DM +16 609 ...	4 27 05	16 33 55	9.07	0.86	1	K1 V	9			
VA 575/LP 415-148 ...	4 27 30	17 23 33	14.45	1.55	5	M2-3	6			Flare Susp. Bin.
VB 82/VA 584/HD 28527/ HR 1427/DM +15 637 ...	4 27 42	16 05 12	4.78	0.17	2	A6 Vn (9) A6 IV (10)		75	21	SB
VB 182/VA 587/L61/O666/ HD 28545/HoA 640/GY 97/ KA 259/VR 22/RaA 248/ DM +15 638 ...	4 27 43	15 37 37	8.94	0.85	1	K0	8			
GH 7-246 ...	4 27 44	14 38 24	14.68	1.56	1	M1	6			
VA 610/LP 415-165 ...	4 28 19	16 17 22	15.13	1.58	5	M4	*			
VB 87/HD 28593/ DM +19 733 ...	4 28 19	20 01 37	8.58	0.74	2	G8 V	9	4	19	Var
VA 617 ...	4 28 30	16 30 42	17.01	1.26	4	K7	*			
VA 622/L69/GH 7-249/ MLC 48 ...	4 28 35	17 36 46	11.94	1.44	1	K7 V	17			
VA 627/L63/GH 7-250/ O727/MLC 49/HoB 105/J285/ DM +17 744 ...	4 28 43	17 36 15	9.54	0.98	1	K2	*			
LP 415-175 ...	4 28 53	15 31 15	14.56		1					Bin.
VA 638/LP415-176/ GH 7-252/O740/HoA 753/VR 23/ RoA 291/WOR 16 ...	4 28 53	15 31 25	12.17	1.47	4	M0.5 (6) M0-1 (7)				
VB 191/VA 645/L62/GH 7-253/ O749/HoA 766/VR 25/KA 283/ LP 415-380/GY 102/J286/ RaA 297 ...	4 29 01	15 23 38	11.08	1.30	1	K5 V (17) M1 (7)				
VA 657/LP 415-187 ...	4 29 14	17 33 34	15.25	1.57	5	M2	6			
VB 90/HR 1436/ HD 28736/DM + 5 674 ...	4 29 25	5 18 15	6.40	0.41	2	F3 V	8	15		
VA 673/L70/EG 38/MLC 50/ HZ 9/GH 7-255/LP 415-186 ...	4 29 30	17 38 45	13.97	0.33	1	M1 (6) DA+dMe (16)				
VA 674 ...	4 29 35	17 47 59	15.66	1.39	4	K9	*			
VB 91/VA 684/HD 28783/ DM +15 646 ...	4 29 58	15 54 05	8.94	0.88	2	K1 V	9			Var Bin?
VB 92/VA 692/HD 28805/ GH 7-258/O816/DM +15 647 ...	4 30 08	15 42 53	8.66	0.74	1	G8 V	9	5	19	Var?
L74 ...	4 30 22	23 53 12	12.62	1.52	1	M2	*			

TABLE 2A—*Continued*

Name	R.A. (1950)	Decl. (1950)	m_v	$B-V$	Ref.	Sp.	Ref.	V	Ref.	Notes
VB 93/VA 712/HD 28878/										
O855/DM +16 620	4 30 45	16 39 32	9.40	0.89	1	K2 V	9			Var?
VA 717	4 30 54	15 32 30	18.37	1.66	4	M6	*			
										Var δ Scuti
VB 95/VA 725/HR 1444/										86 ρ Tau
HD 28910/DM +14 720	4 31 00	14 44 28	4.66	0.24	2	A8 Vn	9	125	21	SB2
										Bin.
VB 96/VA 727/DM +14 721	4 31 08	15 03 37	8.51	0.84	2	K0 IV–V	9	4	19	Var
VB 183/VA 747/HD 28977/										
VR 28/HoA 914/RaA 363/										
KA 324/GY 110/DM +15 650	4 31 39	15 43 56	9.69	0.91	2	K2 V	9			
VB 97/VA 748/HD 28992/									6	11	
DM +15 651	4 31 44	15 24 08	7.94	0.63	2	G1 V	9	7	19	Var
VA 751/O913/DM +17 751	4 31 48	17 38 46	7.95	0.40	1	F4	*			
VA 763/LP 415-382	4 32 37	15 17 52	16.13	1.62	5	M5	*			Susp. Bin.
VB 184/L76/DM +16 630	4 33 08	16 26 24	10.83	1.26	1	K7	*			
VB 99/VA 778/HD 29159/										
DM +15 654	4 33 14	15 33 00	9.37	0.87	1	K1 V	9			
VB 122/HD 30810AB/										
DM +10 654	4 48 26	10 59 03	6.76	0.54	2	F7+F7	14	<6	15	Bin.
L104/J348	4 58 46	13 51 42	11.39	1.36	1	K8	*			

TABLE 2B

POTENTIAL HYADES STARS IN OUR SURVEY

Name	R.A. (1950)	Decl. (1950)	m_v	$B-V$	Ref.	Sp.	Ref.	V	Ref.	Notes
VB 22; VA 108	$4^h14^m47^s$	16°49′35″	8.34	0.77	2	G8V	9			SB1
VB 30; VA 182	4 17 08	13 54 58	5.59	0.28	2	F0V	9	109		SB1?, Var?
VB 52; VA 319	4 21 36	16 46 19	7.80	0.60	2	G1V	9	8	18	
VB 73; VA 495	4 25 55	17 10 35	7.85	0.61	2	G1V	9	7	18	
VB 77; VA 536	4 26 27	17 26 11	7.05	0.50	2	F7V	9	25	15	SB1
VB 79; VA 547	4 26 38	17 47 06	8.96	0.83	2	K0V	9	3.5	11	
VB 80; VA 569	4 27 17	15 31 49	5.58	0.32	2	F0V		134		SB
VB 83; VA 589	4 27 48	15 35 05	5.48	0.26	2	Am	9	21		Bin.
VB 85; VA 597	4 27 55	16 02 30	6.51	0.43		F5V	9	15		
VB 89; VA 644	4 29 00	15 44 45	6.02	0.34	2	F2Vn	9	109		SB1, Var

NOTE.—The star names are coded according to the following conventions: EG: Eggen and Greenstein 1965*a*, *b*; GH: Giclas *et al.* 1962; GY: Gyllenberg 1931; H: Hanson 1975; Ho: Holmberg 1944; Hz: Hertzsprung 1947; HTK: Luyten as quoted by Herbig 1962; HZ: Humason and Zwicky; J: Johnson *et al.* 1962; KA: Kapteyn and de Sitter 1904; L: Pels *et al.* 1975; LP: Luyten *et al.* 1981; MLC: Murray *et al.* 1966; O: Osvald 1954; Ra: Ramberg 1941; VA: van Altena 1969; VB: van Bueren 1952; VR: van Rhijn and Raymond 1934; VYS: Vyssotsky 1956; WOR: Worley 1962.

REFERENCES.—(1) Upgren 1974; Upgren and Weiss 1977; Upgren, Weiss, and DeLuca 1979; Weiss, DeLuca, and Upgren 1979; Weiss and Upgren 1982; (2) Johnson *et al.* 1962; (3) Hanson 1975; (4) van Altena 1969; (5) Stauffer 1982; (6) Pesch 1968, 1972; (7) Herbig 1962; (8) Blanco *et al.* 1970; (9) Morgan and Hiltner 1965; (10) Cowley *et al.* 1969; (11) Lockwood *et al.* 1984; (12) Treanor 1960; (13) Wilson 1963; (14) Hoffleit and Jasheck 1982; Hoffleit, Saladiga, and Wlansk 1984; (15) Kraft 1965; (16) Eggen and Greenstein 1965*a*, *b*; (17) Buscombe 1977, 1980, 1981; (18) Soderblom 1983; (19) Duncan *et al.* 1984; (20) Horan 1979; (21) Abt 1975; Abt and Moyd 1973; (22) Gray and Endal 1982.

* Spectral types computed from color index or rotational velocity inferred from modulation of chromospheric emission.

TABLE 3

SUMMARY OF DETECTIONS

	Number of Detections	Pointed Detections	Serendipitous Detections	Distinct Sources
Hyades Members	116	5	111	66
Other Stellar Sources	74	6	68[a]	61
Nonstellar Sources	14	8	6	11
Not Identified Sources	114	...	114	98
Totals	318	...	299	236

[a] Nineteen X-ray sources are identified with Pleiades members. Six X-ray sources are identified with T Tauri stars in the Taurus-Auriga complex previously reported as X-ray sources by Feigelson and De Campli (1981).

objects.[7] Thus we are left with a total of 98 nonidentified X-ray sources in the 63 surveyed fields. Our results are summarized in graphical form in Figures 4–5. Figure 4 shows the H-R diagram of the cluster stars in the 63 IPC images, and a breakdown into spectral types of the detected main-sequence stars is given in Figure 5.

We now consider the problem of mistakenly identifying X-ray detections with Hyades stars. Mistakes can occur when either a spurious detection or a real, unrelated source appears near the position of a Hyades star. Let p be the ratio of the survey area (i.e., the total area of all 2′ radius circles around

[7] The majority of nonstellar identifications are in images taken in the external region of the Hyades cluster; six are serendipitous sources and five are pointed targets. On the other hand, only a small fraction of the stellar objects (six) are pointed targets of the images considered. In § IV, we will consider the X-ray properties of the non-Hyades field stars.
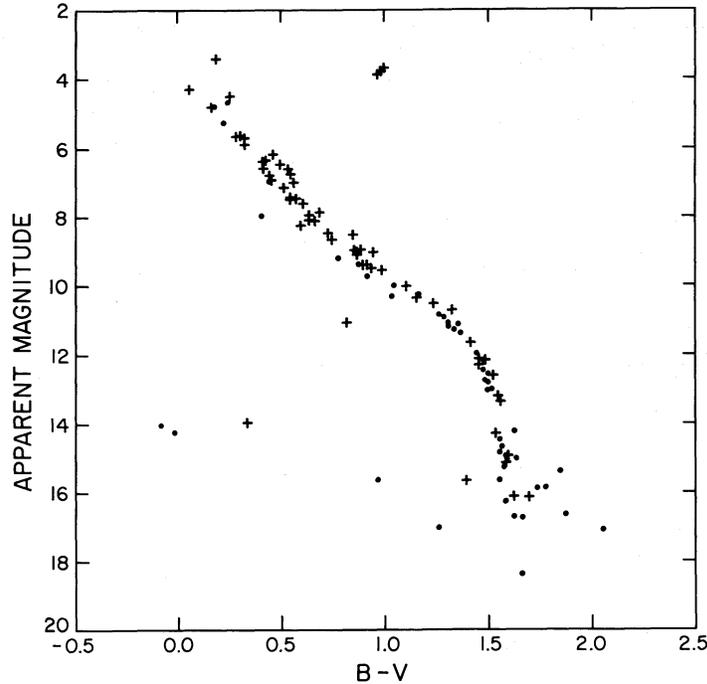
FIG. 4.—H-R diagram for the Hyades stars in the present survey. The crosses indicate stars detected as X-ray sources. Note that the detected white dwarf is a binary system containing a dM star.

Hyades stars, of which there are 250 with repetitions) to the total area of all IPC fields. If we assume that the spurious detections and unrelated sources appear uniformly over the field of view, p is also the probability for a mistaken identification. We expect ~ 38 spurious X-ray detections and ~ 55 unrelated sources[8]; thus, we obtain no mistaken identification of a Hyades star, with a probability $(1-p)^{93}$. Since $p \sim 1.4 \times 10^{-2}$, the probability of obtaining no mistaken identification is ~ 0.27. We therefore recognize that we may have made one or two mistaken identifications.

c) Count Rate, Flux, and Luminosity Computation

Vignetting, detection cell efficiency, and shadowing by the IPC entrance-aperture supports structure were taken into account in order to give the effective broad-band count rate for each detected source, together with its statistical errors. We note that because of the spectral dependence of the mirror response and of the IPC point response function correction, the size of the broad-band detection cell, and the relatively soft stellar spectra, $\sim 30\%$ of the stellar source counts fall outside the broad detection cell. Hence, for the majority of Local, unobscured X-ray detections we have evaluated the count rate by collecting source counts in a circle of 3' radius and background counts in an annulus (centered on the source) defined by an inner radius of 5' and an outer radius of 6'; for the Local obscured X-ray detections, and for those X-ray detections for which only the Map method was used, we have instead used the standard (REV-1) net count rates increased by 25%. We

have applied the same correction to the upper bounds that are evaluated in the detection cell with the Local method (for further details and discussion, see the Appendices).

We have converted from count rates to X-ray fluxes in the 0.16–4.0 keV energy band using a constant conversion factor of 2.0×10^{-11} ergs count^{-1} cm^{-2}. This value was used to allow easy comparison of our results with previously published
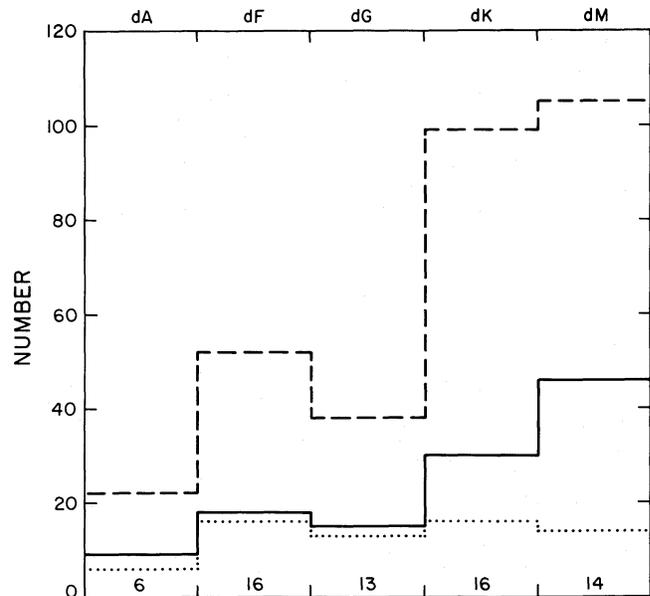
FIG. 5.—Spectral type breakdown of the detections of the main-sequence Hyades stars. The plot shows the spectral distributions of : the complete optical catalog (*dashed line*), those stars which fell into one of the IPC fields of this X-ray survey (*solid line*), and those stars detected as X-ray sources (*dotted line*).

[8] Using the medium-sensitivity survey results of Maccaro *et al.* (1982) extrapolated to the 3 σ detection level, and taking galactic absorption into account, we predict ~ 40 extragalactic sources in our survey. The calculations discussed in § IV indicate an expected total of ~ 15 field stars in our combined field of view.
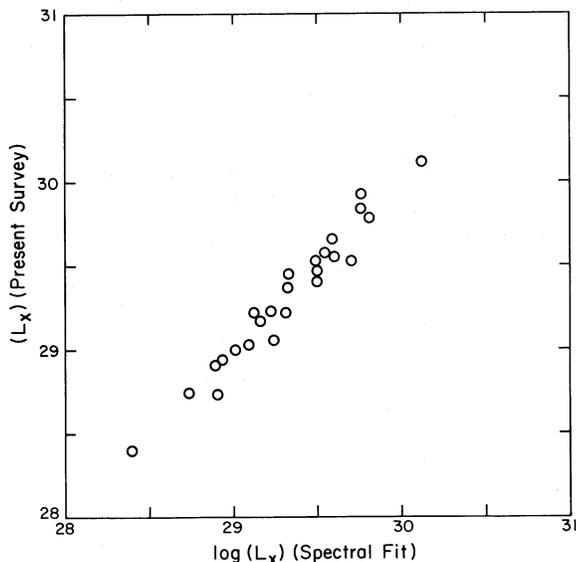
FIG. 6.—Comparison of X-ray luminosities deduced from detailed fit to the IPC spectra (given in abscissa) and of X-ray luminosities deduced from the simple single constant conversion factor approach (given in ordinate). Note the extremely good agreement between the two determinations.

data and is correct for a source temperature of $\sim 3 \times 10^6$ K, with negligible hydrogen column density absorption.[9]

We were able to perform spectral fits using a model of thermal, solar-abundance, plasma emission (Raymond and Smith 1977) for 27 distinct X-ray sources. These fits, whose discussion is deferred to a forthcoming paper, allow us to verify *a posteriori* the agreement between the values of X-ray luminosity derived using the constant conversion factor and the corresponding values derived with a complete fitting procedure, as can be seen from Figure 6. The conversion factor from count rate to luminosity, assuming a common distance of 45 pc (Hanson 1975) for all cluster members, is 4.86×10^{30} ergs count^{-1}. We note that a detailed analysis of the spectra of three strong Hyades X-ray sources demonstrated that single-component thermal plasma models do not fit appropriately the IPC pulse-height spectra (Stern, Antiochos, and Harnden 1986). However, these more sophisticated models did not significantly affect the computation of flux conversion.

The mean X-ray luminosities (along with their statistical uncertainties), and the 3 σ upper limits inferred from our survey, are listed in Table 4A, for the certain Hyades members, and in Table 4B for the 10 stars whose membership is questionable. The estimated overall error in the X-ray luminosities is a factor ~ 2 and consists of statistical errors (less than 40% for the 2.5 σ sources), systematic errors in instrument calibrations ($\leq 10\%$, Harnden *et al.* 1984), errors due to the individual cluster member distance ($< 100\%$), and systematic errors in converting count to flux due to the assumed source temperature ($\leq 40\%$).

IV. X-RAY SOURCES IDENTIFIED WITH FIELD STARS IN THE HYADES REGION

The large number of field stars (i.e., non-Hyades members) identified with X-ray sources in the Hyades region suggested

[9] This latter assumption is justified by the modest Hyades member distance. Recently, Westergaard *et al.* (1985), using broad-band *EXOSAT* observation of stars in the Hyades region, quoted a value of $1-2 \times 10^{19}$ cm^{-2} for N_H which, if used, would only increase the conversion factor by $\sim 2\%$.

that we investigate whether the number of these X-ray sources is in agreement with expectations. We exclude from the following discussion 19 X-ray sources that we have identified with certain Pleiades cluster members and eight X-ray sources identified with T Tauri stars in the Taurus-Auriga complex.

The predicted number of detectable field stars in this survey has been computed using (*a*) the Galaxy model of Bahcall and Soneira (1980), (*b*) the values of the mean limiting sensitivity of each field, and (*c*) the best current (1986 spring) estimates of the X-ray luminosity functions for each spectral type of the nearby dwarf stars. A detailed description of the procedure employed can be found in Favata *et al.* (1988).

We have performed our computation using the area of the IPC field of view inside the ribs ($32' \times 32'$) and excluding the central $5'$ (to remove the bias introduced by the targeted sources). We have also taken the IPC fields as independent of one another; that is, we have considered the overlap regions of different IPC fields, and the stars falling in these regions, more than once. The results of these calculations, when compared with the actual number of X-ray detections identified with each distinct spectral type, indicated an excess for the dG stars: We predict 0.85 dG stars, while the observed number of detections identified with G stars is five. We also performed a similar comparison by considering the full $1° \times 1°$ IPC field of view. (Although the inclusion of the region outside the window support structure nearly doubles the geometric aperture, the effective aperture is increased by a lesser amount due to the lower sensitivity of this region farther from the telescope axis.) The expected number of detections for the entire field can be conservatively evaluated increasing the expectation computed inside the ribs by $\sim 30\%$. Thus in the total field of view we predict ~ 1.1, while the number of detections identified with G stars is 12.

The above comparisons show an excess of X-ray detections identified with dG stars and suggest that X-ray emission can furnish a further independent criterion for cluster membership in analogy to the proposal of Kraft and Greenstein (1969) for using the presence of Ca II emission as a criterion for Pleiades membership. A closer examination of this sample of dG stars shows that for the majority of detections identified with these stars (i.e., at least eight of 12 detections involving five distinct stars), there is substantial disagreement between different authors and different methodologies for establishing cluster membership. (For the remaining stars, there is no definitive information for assessing their Hyades cluster membership.)

We note in this context that 45 of the 248 stars rejected by Hanson (1975) (and because of that not included in our optical catalog) have been accepted as cluster members by van Altena (1969). (The two authors investigate nearly identical regions of the sky.) This sample of the 45 rejected stars contains 10 G stars, five of which appear in the present survey. For these five G stars we have computed an X-ray luminosity function (assuming that they are at the Hyades cluster distance) and have verified (using a nonparametric statistical test, cf. § V) that the luminosity function for this sample is indistinguishable from that of the Hyades G stars.

We have also computed the expected number of X-ray sources associated with solar-like survey stars as a function of X-ray flux, following the method of Favata *et al.* (1988). The Bahcall and Soneira (1980) model of our Galaxy and the X-ray luminosity function of Maggio *et al.* (1987) for the nearby solar-like stars have been adopted. In Figure 7 we show the prediction (*solid line*) compared to the 12 observations of (five)

TABLE 4A

SUMMARY OF X-RAY LUMINOSITIES FOR CERTAIN HYADES MEMBERS

Name	L_x [ergs s^{-1}]	1 σ error on L_x	Flux Flag[a]	RECO[b]
Hz 2411	$<0.34 \times 10^{29}$		LB	Y
VB 170	$<0.47 \times 10^{29}$		LB	
L7	$<0.38 \times 10^{29}$		LB	
VB 8	0.18×10^{30}	0.16×10^{29}	WM	
L14	$<0.54 \times 10^{29}$		LB	
H14	$<0.36 \times 10^{29}$		LB	
VB 15	0.13×10^{30}	0.31×10^{29}	MB	Y
VB 19	0.14×10^{30}	0.39×10^{29}	MB	Y
VA 95	$<0.40 \times 10^{29}$		LB	
VA 118	$<0.68 \times 10^{29}$		LB	Y
VA 122	$<0.67 \times 10^{29}$		LB	Y
VA 127	$<0.21 \times 10^{29}$		LB	
VA 131	$<0.89 \times 10^{29}$		LB	Y
VB 24	0.11×10^{30}	0.44×10^{29}	MB	Y
VA 135	0.15×10^{30}	0.16×10^{29}	LC	Y
VB 27	0.55×10^{29}	0.88×10^{28}	WM	Y
VA 162	$<0.45 \times 10^{29}$		LB	
VB 28	0.35×10^{30}	0.32×10^{29}	WM	Y
VB 29	0.15×10^{30}	0.20×10^{29}	WM	Y
VB 31	0.19×10^{30}	0.31×10^{29}	WM	
VB 33	$<0.33 \times 10^{29}$		LB	Y
VB 34	0.13×10^{30}	0.27×10^{29}	MB	Y
VA 203	$<0.36 \times 10^{29}$		LB	
VB 35	0.11×10^{30}	0.44×10^{29}	MB	Y
VB 36	0.66×10^{29}	0.22×10^{29}	MB	Y
VA 213	$<0.58 \times 10^{29}$		LB	
VB 39	0.21×10^{30}	0.37×10^{29}	LC	
VA 216	$<0.70 \times 10^{29}$		LB	Y
VB 38	0.36×10^{29}	0.13×10^{29}	MB	
VA 241	$<0.32 \times 10^{29}$		LB	Y
VA 242	$<0.37 \times 10^{29}$		LB	
VB 39	0.18×10^{30}	0.39×10^{29}	LC	
VB 40	0.31×10^{30}	0.14×10^{29}	WM	
VB 41	0.10×10^{30}	0.27×10^{29}	MB	
VA 260	$<0.22 \times 10^{29}$		LB	
VA 262	$<0.49 \times 10^{29}$		LB	
VB 43	0.58×10^{29}	0.20×10^{29}	MB	Y
VB 45	0.69×10^{29}	0.28×10^{29}	MB	
VA 275	0.50×10^{29}	0.88×10^{28}	WM	Y
VB 173	0.69×10^{29}	0.20×10^{29}	MB	Y
VB 46	0.35×10^{29}	0.68×10^{28}	WM	
VA 282	$<0.49 \times 10^{29}$		LB	
VA 288	0.13×10^{30}	0.92×10^{28}	WM	
VA 292	$<0.66 \times 10^{29}$		LB	Y
VA 294	$<0.51 \times 10^{29}$		LB	Y
VA 297	$<0.51 \times 10^{29}$		LB	
VB 47	0.41×10^{29}	0.17×10^{29}	MB	Y
VB 49	0.11×10^{30}	0.43×10^{29}	MB	Y
VB 50	0.58×10^{30}	0.19×10^{29}	WM	
VB 174	$<0.56 \times 10^{29}$		LB	Y
VB 51	$<0.81 \times 10^{29}$		LB	Y
VA 321	$<0.54 \times 10^{29}$		LB	Y
VA 326	$<0.40 \times 10^{29}$		LB	Y
VA 329	$<0.69 \times 10^{29}$		LB	
VA 334	0.55×10^{29}	0.83×10^{28}	WM	Y
VB 175	$<0.31 \times 10^{29}$		LB	
VA 351	0.15×10^{30}	0.50×10^{29}	LC	
VB 56	0.76×10^{29}	0.17×10^{29}	MB	Y
VB 57	0.35×10^{30}	0.40×10^{29}	LC	
VB 176	0.74×10^{29}	0.18×10^{29}	MB	Y
VA 362	$<0.37 \times 10^{29}$		LB	
VA 366	0.54×10^{29}	0.11×10^{29}	LC	
VA 368	$<0.45 \times 10^{29}$		LB	
VA 382	0.29×10^{29}	0.73×10^{28}	MB	
VA 383	0.32×10^{29}	0.10×10^{29}	MB	Y
VB 59	0.28×10^{30}	0.17×10^{29}	LC	
VB 141	0.13×10^{31}	0.27×10^{29}	LC	
VB 63	0.18×10^{30}	0.11×10^{29}	WM	
VB 64	0.11×10^{30}	0.88×10^{28}	WM	
VA 410	0.18×10^{30}	0.27×10^{29}	MB	Y
VA 420	$<0.32 \times 10^{29}$		LB	Y
VA 444	0.30×10^{29}	0.13×10^{29}	LC	
VB 65	0.87×10^{29}	0.12×10^{29}	LC	
VB 179	0.59×10^{29}	0.20×10^{29}	MB	Y
VB 189	$<0.21 \times 10^{29}$		LB	Y
VB 68	0.72×10^{29}	0.19×10^{29}	LC	
VA 486	0.18×10^{30}	0.43×10^{29}	MB	Y
VB 71	0.71×10^{30}	0.22×10^{29}	WM	
VA 490	$<0.38 \times 10^{29}$		LB	Y
VB 72	0.26×10^{29}	0.68×10^{28}	MB	
VB 190	0.15×10^{30}	0.25×10^{29}	LC	
VA 502	$<0.22 \times 10^{29}$		LB	
VB 75	0.16×10^{30}	0.14×10^{29}	WM	
VA 512	0.72×10^{29}	0.17×10^{29}	MB	
VA 529	$<0.47 \times 10^{29}$		LB	
VB 76	$<0.49 \times 10^{29}$		LB	
VB 78	0.64×10^{29}	0.12×10^{29}	MB	Y
VB 181	0.32×10^{29}	0.11×10^{29}	LC	
VA 559	$<0.19 \times 10^{30}$		LB	Y
VB 180	0.97×10^{29}	0.28×10^{29}	MB	Y
VA 575	$<0.67 \times 10^{29}$		LB	
VB 82	$<0.19 \times 10^{29}$		LB	
VB 182	0.39×10^{29}	0.92×10^{28}	MB	
GH 7-24	$<0.66 \times 10^{29}$		LB	
VA 610	0.24×10^{29}	0.68×10^{28}	MB	
VB 87	$<0.12 \times 10^{30}$		LB	Y
VA 617	$<0.26 \times 10^{29}$		LB	Y
VA 622	$<0.61 \times 10^{29}$		LB	
VA 627	0.82×10^{29}	0.12×10^{29}	WM	
LP 415-175	$<0.54 \times 10^{29}$		LB	Y
VA 638	$<0.51 \times 10^{29}$		LB	Y
VB 191	$<0.64 \times 10^{29}$		LB	Y
VA 657	$<0.31 \times 10^{29}$		LB	Y
VB 90	0.11×10^{30}	0.12×10^{29}	LC	
VA 673	0.33×10^{29}	0.15×10^{29}	LC	
VA 674	0.24×10^{29}	0.73×10^{28}	MB	
VB 91	0.53×10^{29}	0.10×10^{29}	MB	
VB 92	0.73×10^{29}	0.24×10^{29}	MB	Y
L74	0.16×10^{30}	0.22×10^{29}	MB	Y
VB 93	0.83×10^{29}	0.22×10^{29}	WM	Y
VA 717	$<0.36 \times 10^{29}$		LB	
VB 95	$<0.32 \times 10^{29}$		LB	
VB 96	0.69×10^{29}	0.27×10^{29}	MB	
VB 183	$<0.63 \times 10^{29}$		LB	
VB 97	0.12×10^{30}	0.26×10^{29}	LC	
VA 751	$<0.19 \times 10^{30}$		LB	Y
VA 763	0.80×10^{29}	0.24×10^{29}	MB	
VB 184	$<0.76 \times 10^{29}$		LB	
VB 99	$<0.71 \times 10^{29}$		LB	Y
VB 122	0.27×10^{30}	0.44×10^{29}	MB	Y
L194	$<0.38 \times 10^{29}$		LB	

TABLE 4B

SUMMARY OF X-RAY LUMINOSITIES FOR POTENTIAL HYADES MEMBERS

Name	L_x (ergs s^{-1})	1 σ error on L_x	Flux Flag[a]	RECO[b]
VB 22[c]	0.28×10^{31}	0.54×10^{29}	LC	
VB 30	$<0.63 \times 10^{29}$		LB	Y
VB 52	0.12×10^{30}	0.34×10^{29}	LC	
VB 73	0.13×10^{30}	0.28×10^{29}	LC	
VB 77	0.33×10^{30}	0.49×10^{29}	MB	Y
VB 79	0.88×10^{29}	0.17×10^{29}	MB	Y
VB 80	0.74×10^{29}	0.29×10^{29}	MB	Y
VB 83	$<0.42 \times 10^{29}$		LB	Y
VB 85	0.32×10^{30}	0.37×10^{28}	LC	
VB 89	0.43×10^{29}	0.17×10^{29}	MB	

[a] Flag indicating how the X-ray luminosity is evaluated (cf. Appendix): MB = from the "Map" cell count rate increased by 25% (see Appendix B) for sources partially obscured or detected only with the "Map" method; LC = from the "Local" count rate in a 3' radius circle for sources detected with the "Local" method; LB = from the "Local" cell count rate increased by 25% (only for upper limits); WM = weighted mean of the corrected values for sources observed more than once.

[b] Y means that X-ray luminosity is derived in presence of potential source shadowing (cf. Appendix).

[c] This value of the X-ray luminosity has been derived during a flare (cf. Stern *et al.* 1983).

G field stars, and to the four observations of (four) G stars for which there is no conclusive data on their Hyades membership. While the excess with respect to the prediction is evident in the first case, the removal of the eight X-ray detections identified with the five G stars for which there is disagreement about Hyades membership also completely removes the excess. We conclude that these results strongly support our hypothesis that these five G stars are Hyades members.
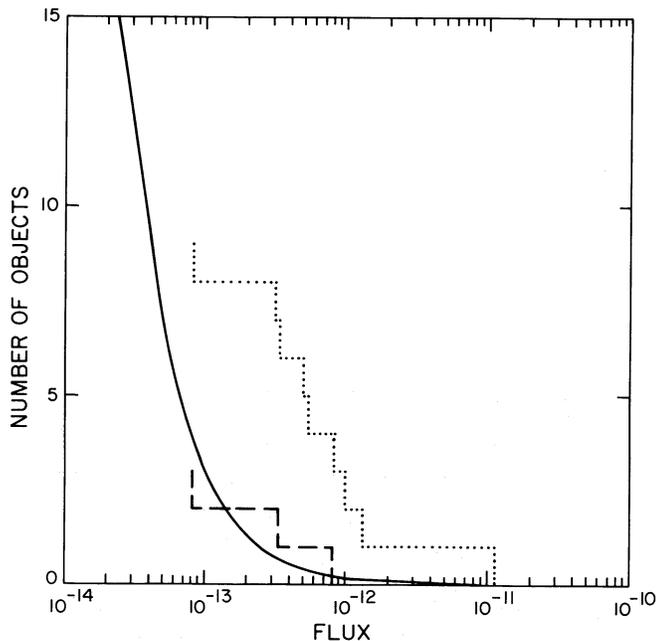
FIG. 7.—Expected number of solar-like field stars as function of the limiting sensitivity (*solid line*), observed number of non-Hyades solar-like stars including the stars whose membership is questionable (*dotted line*), and observed number of non-Hyades solar-like stars but excluding those stars whose membership is questioned (*dashed line*).

V. X-RAY SOURCES IDENTIFIED WITH HYADES CLUSTER MEMBERS

In this section we consider the X-ray sources identified with Hyades cluster members (using the identification criteria of § II). Our particular interest lies in the dependence of stellar X-ray emission levels on stellar age and spectral type. In order to compare our results with those of previous studies, we took advantage of techniques recently applied to the astronomical realm to construct maximum likelihood luminosity distribution functions which take into account both flux measurements and upper bounds (Avni *et al.* 1980; Schmitt 1985), as well as comparisons of sample properties using nonparametric two-sample tests in presence of data containing upper bounds (Schmitt 1985; Feigelson and Nelson 1985).

We emphasize that because of the different ranges of stellar distances for the samples we have considered, the distributions of the limiting X-ray luminosity sensitivities are different. For example, the minimum detectable X-ray luminosities are larger for the Pleiades than for the Hyades, and larger for the Hyades than for the field stars. In such a case of "censored data," the use of the permutational variance in applying nonparametric two-sample tests is strictly speaking not appropriate (cf. Schmitt 1985; Feigelson and Nelson 1985). Hence, in order to minimize the dependence of test outcomes on the censoring distribution, we have applied the nonparametric two-sample Peto-Prentice generalized Wilcoxon test, using the functional form for the variance as derived by Latta (1981) and applied by Feigelson and Nelson (1985). When we refer to the generalized Wilcoxon test in the following, we mean the test described by these latter authors.

a) Main-Sequence Stars—Luminosity Functions

To compare our results with those of published X-ray surveys of nearby dwarf stars (Schmitt *et al.* 1985; Maggio *et al.* 1987; Bookbinder 1985) and of other coeval groups of stars (Caillault and Helfand 1985; Micela *et al.* 1985; Smith, Pravdo, and Ku 1983), we will consider the dwarf stars in four distinct color intervals, namely: $(B-V) = 0.0$–0.5, dA and early dF stars; $(B-V) = 0.51$–0.80, solar-like stars; $(B-V) = 0.81$–1.45, dK stars; and $(B-V) > 1.45$, dM stars.

i) dA and Early dF Stars

The A8 Vn (Cowley *et al.* 1969) or F0 V (Hoffleit 1982) star 71 Tau is the strongest X-ray source in the Hyades [log (L_x) = 30.11]. The star 71 Tau appears peculiar because its X-ray emission is quite intense when compared to the X-ray emission of any other Hyades star or to the A stars reported in previous surveys (Cash and Snow 1982; Golub *et al.* 1983; Schmitt *et al.* 1985); the only A star comparable to 71 Tau is HzII 1384 [log (L_x) = 30.12], detected in the surveys of the Pleiades cluster (Caillault and Helfand 1985; Micela *et al.* 1985). As discussed earlier by Stern *et al.* (1981), the behavior of 71 Tau may be related to the star being a very fast rotator ($v \sin i = 160$ km s^{-1}, Abt 1975) and a δ Scuti variable with a fundamental period of 3.9 hr (Horan 1979); an unpublished survey of six other δ Scuti variables performed with *Einstein*, motivated by the 71 Tau detection, however, failed to detect X-ray emission in any other member of the δ Scuti class. The star 71 Tau is also a member of a spectroscopic binary system; Peterson *et al.* (1981), using the technique of lunar occultations, resolved the system and identified the companion as a G4 V star (with an accuracy of one spectral subtype) with $m_v = 8.1$ mag. However, the intensity of X-ray emission cannot be explained easily by the presence of a dG companion because
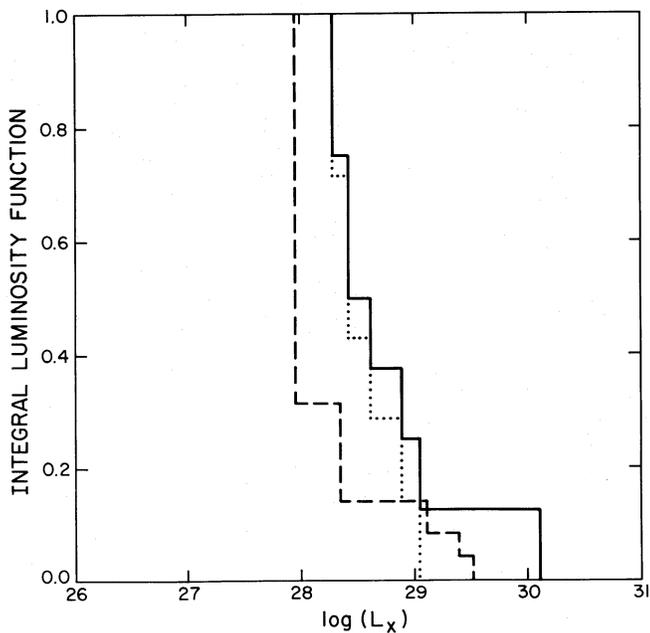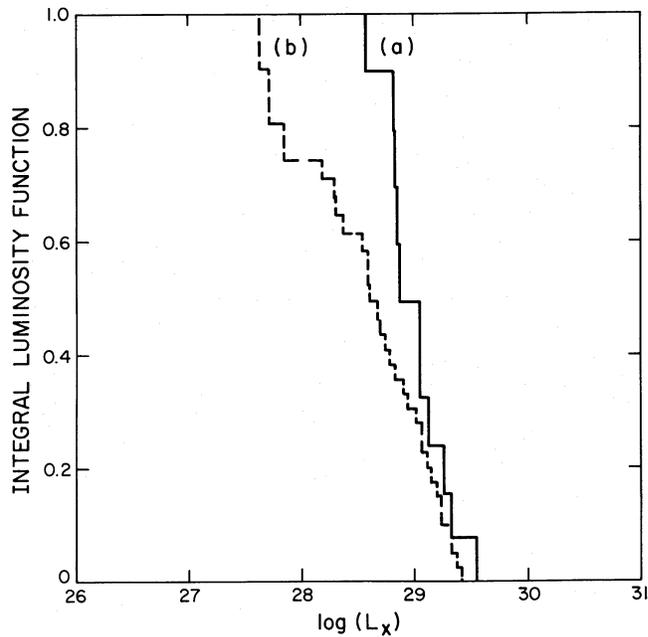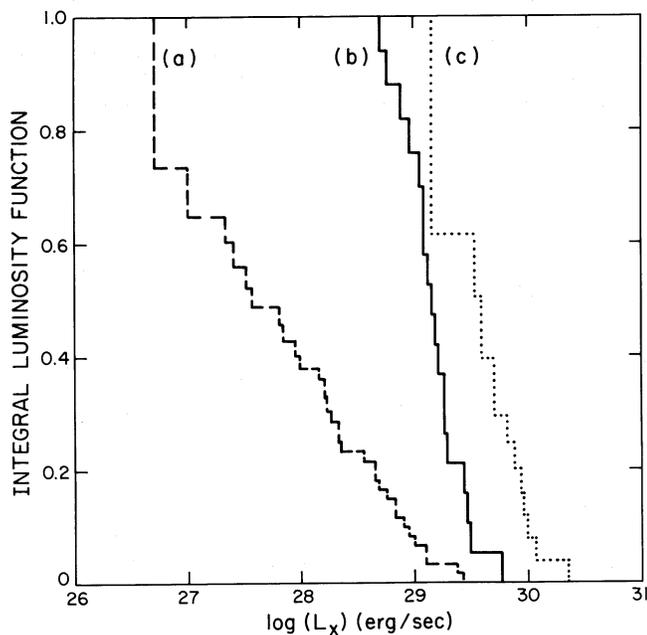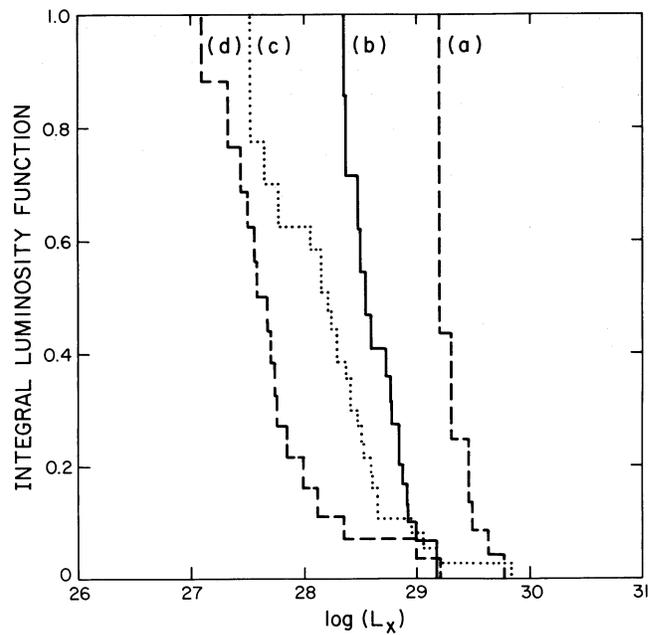
FIG. 8a

FIG. 8b

FIG. 8c

FIG. 8d

FIG. 8.—Integral X-ray luminosity functions for (*a*) the early A stars of the Hyades (*solid line*), the Hyades excluding 71 Tau (*dotted line*), and the field stars in the same range of *B* − *V* (data from Schmitt *et al.* 1985; *dashed line*); (*b*) the late A and early F stars of the Hyades (*solid line*) and the field stars in the same range of *B* − *V* (data from Schmitt *et al.* 1985; *dashed line*); (*c*) the solar-like stars of the Hyades (*solid line*), the Pleiades (data from Micela *et al.* 1985; *dotted line*), and the field stars in the same range of *B* − *V* (from Maggio *et al.* 1987; *dashed line*); (*d*) the K stars of the Pleiades (*dashed curve* [*a*]), *the Hyades* (*solid line*), the young disk nearby population (*dotted line*), and the old disk nearby population (*dashed curve* [*d*]); (*e*) the M stars of the Hyades (*solid line*), the young disk nearby population (*dotted line*), and the old disk nearby population (*dashed line*).

the observed luminosity is too intense even for a typical Hyades G dwarf.

We have detected X-ray emission from 16 of 21 dwarf stars in the *B* − *V* range between 0.00 and 0.50; for the remaining five stars, we have computed 3 σ upper limits. This compares with the 17 out of 25 stars of spectral type A2–F8 detected in the cluster central region survey (Stern *et al.* 1981) with a median of log (*L*$_x$) ∼ 28.7.

To compare our results with those of the X-ray survey of nearby A and early F stars by Schmitt *et al.* (1985), we have separately considered two *B* − *V* intervals (0.00–0.30) and (0.31–0.50), and have taken care to exclude all Hyades members sampled in the original survey of Schmitt *et al.* (1985).

Our sample of stars in the range *B* − *V* = (0.00–0.30) consists of eight stars (five detections and three upper bounds), all
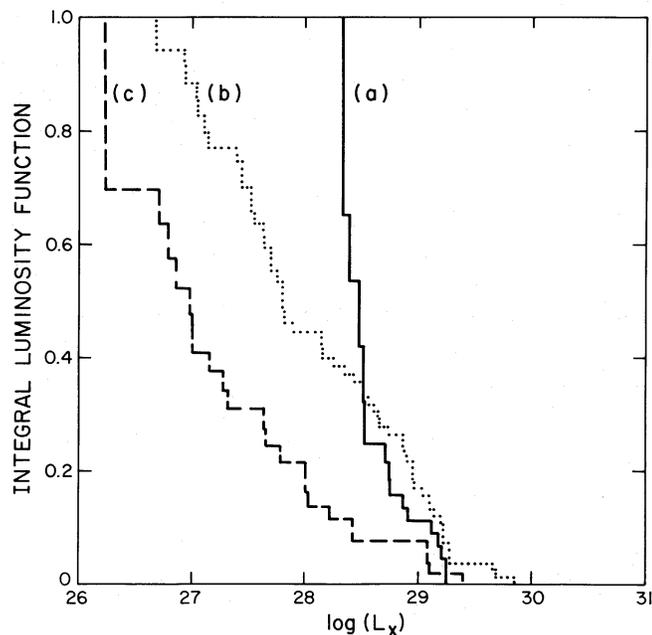
FIG. 8e

members of multiple systems. We note that the majority of these stars are Am or δ Scuti variables, and that the peculiarity of these stars could affect the comparison with the (presumably normal) stars surveyed by Schmitt *et al.* (1985). In Figure 8a, the integral X-ray luminosity function of these early A Hyades members is plotted (twice: solid line with 71 Tau included, dotted line with 71 Tau excluded) together with the luminosity function for the binary stars of Schmitt *et al.* (1985), which comprise 28 objects (five detections + 23 upper bounds). We have applied a nonparametric generalized Wilcoxon test to the first and last of these distributions and find them to be indistinguishable. (The null hypothesis that they are drawn from the same parent distribution can be rejected only at the 78% confidence level.) We have also computed the values of the mean of $\log (L_x)$:

$$\langle \log (L_x) \rangle_{\text{Hyades}} = 28.75 \begin{array}{c} +0.16 \\ -0.20 \end{array}$$

$$\langle \log (L_x) \rangle_{\text{Field}} = 28.25 \begin{array}{c} +0.10 \\ -0.12 \end{array}.$$

Here, and in the following, the 68% (1 σ) errors on $\langle \log (L_x) \rangle$ are computed using the bootstrap technique (cf. Schmitt 1985 and references therein) using 200 bootstrap replications. The above Hyades values have been computed with 71 Tau included. To assess the effects of this source on the above comparison, we have recomputed the value of $\langle \log (L_x) \rangle$ without this "peculiar" star, obtaining $\langle \log (L_x) \rangle = 28.57$ [28.69, 28.46]. Thus, the inclusion of 71 Tau hardly matters, and we conclude that the distributions of Hyades and nearby field A stars are essentially indistinguishable, as expected from the fact that the A stars in the Hyades, like nearby field A stars, are quite evolved.

In Figure 8b we show the integral X-ray luminosity function for Hyades stars (single and binary stars combined) with $B - V = (0.31 – 0.50)$, and compare it to the luminosity function for the nearby ($d < 30$ pc) single and binary field stars (Schmitt

et al. 1985) in the same range of $B - V$. Again using the nonparametric generalized Wilcoxon test, we find the two distributions to be indistinguishable (null hypothesis rejection confidence level of only 61%). The values of the mean of $\log (L_x)$ and their 68% confidence level errors using a bootstrap technique are

$$\langle \log (L_x) \rangle_{\text{Hyades}} = 28.99 \begin{array}{c} +0.09 \\ -0.07 \end{array}$$

$$\langle \log (L_x) \rangle_{\text{Field}} = 28.56 \begin{array}{c} +0.10 \\ -0.02 \end{array}.$$

ii) *Solar-like Stars*

It is useful to compare the data presented here for solar-like stars ($0.51 \leq B - V \leq 0.80$) with the results of an *Einstein* survey of the nearby solar-like stars (Maggio *et al.* 1987) and with those of the *Einstein* Pleiades surveys (Caillault and Helfand 1985; Micela *et al.* 1985). We have detected 17 of 19 Hyades members in the range of $B - V$ under study, while Micela *et al.* (1985) report X-ray luminosities for 26 Pleiades stars (13 detections and 13 upper limits) in the same color interval.[10] This compares with 11 out of 13 Hyades members of spectral type G0–G8 detected in the previous survey limited to the central region of the cluster (Stern *et al.* 1981), with a median of $\log (L_x) \sim 29.1$. Using both the detections and upper limits, we have plotted the integral X-ray luminosity functions for both the Hyades and the Pleiades solar-like stars in Figure 8c, where we display for comparison the luminosity function for the nearby ($d < 25$ pc) solar-like field stars from Maggio *et al.* (1987). Because, in general, there is not enough information in the cases of the Hyades and Pleiades for assessing the multiplicity of the optical counterparts, we have combined the samples of single and binary stars in performing these comparisons. With the Wilcoxon test, we find evidence that the samples of Hyades and Pleiades X-ray sources are different (null hypothesis rejected at the 97.8% confidence level). The same test applied to a comparison of the Hyades and the field stars indicates a more definite difference (rejection of the analogous null hypothesis at the 99.5% confidence level).

The mean values of $\log (L_x)$ for the three samples considered above are

$$\langle \log (L_x) \rangle_{\text{Pleiades}} = 29.54 \begin{array}{c} +0.06 \\ -0.07 \end{array}$$

$$\langle \log (L_x) \rangle_{\text{Hyades}} = 29.16 \begin{array}{c} +0.05 \\ -0.07 \end{array}$$

$$\langle \log (L_x) \rangle_{\text{Field}} = 27.71 \begin{array}{c} +0.15 \\ -0.09 \end{array}.$$

This confirms the trend of decreasing $\langle \log (L_x) \rangle$ with stellar age previously discussed by, among others, Vaiana (1983), Stern (1983), Caillault and Helfand (1985), and Micela *et al.* (1985).

For the sake of completeness, we have also considered the sample of Hyades dG stars augmented by the five dG stars whose Hyades membership is questioned (cf. § IV). The

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[10] In the following, we reference the data of the Pleiades survey by Micela *et al.* (1985), because that survey—like the present one and the survey of field solar-like stars by Maggio *et al.* (1987)—was derived using the REV-1 system, while the Pleiades survey of Caillault and Helfand (1985) utilized an earlier reduction system and did not take individual upper limits into account.

enlarged sample (with 22 of 24 dG stars detected) has both a mean log $(L_x)(= 29.20$ [29.26, 29.14]) and a luminosity function which are indistinguishable from those of the more restricted sample.

iii) *K Stars*

We have detected 16 of 30 dK stars in our catalog and, using both the detection and the upper bounds, have computed the integral X-ray luminosity function shown as (*b*) in Figure 8*d*. Also shown for comparison are luminosity functions for (*c*) the young disk and (*d*) the old disk field dK stars (single and binary, from Bookbinder 1985), and for (*a*) the Pleiades dK stars of Micela *et al.* (1985).

While the sample of the Hyades solar-like stars is complete, the sample of the Hyades dK stars is not, due to the lack of optical completeness of the catalog in the outer regions of the cluster. In comparing the results of the Hyades dK stars with those of the field dK stars and of the Pleiades dK stars we must demonstrate that the incompleteness of the optical catalog of the Hyades and Pleiades clusters does not affect our results. To investigate possible bias effects, we have checked whether the $B-V$ distributions of the three samples under examination are compatible with their having been drawn from the same parent population. The results of a two-sample nonparametric statistical test indicate that the samples considered above have $B-V$ distributions compatible with a single parent distribution (with rejection confidence levels ranging from 46% to 84%), and that possible differences in the X-ray intensity of their emission cannot be explained in terms of bias in the composition of the optical samples.

On the basis of these results, we can compare the properties of the X-ray luminosity functions for these samples

$$\langle \log (L_x)\rangle_{\text{Pleiades}} = 29.30 \begin{array}{l} +0.05 \\ -0.03 \end{array}$$

$$\langle \log (L_x)\rangle_{\text{Hyades}} = 28.62 \begin{array}{l} +0.06 \\ -0.05 \end{array}$$

$$\langle \log (L_x)\rangle_{\text{Yd}} = 28.18 \begin{array}{l} +0.10 \\ -0.10 \end{array}$$

$$\langle \log (L_x)\rangle_{\text{Od}} = 27.71 \begin{array}{l} +0.11 \\ -0.09 \end{array},$$

where we quote the 1 σ error computed via the bootstrap technique using 200 bootstrap replications. These values again indicate a clear decline of X-ray luminosity with stellar age.

Continuing our investigation, we have applied the nonparametric two-sample generalized Wilcoxon test to the luminosity functions of the Hyades dK stars and the nearby dK stars. We find these two distributions to be rather dissimilar (null hypothesis rejected at 99.3% confidence level) but are less confident of any difference between the Hyades dK stars and the young disk dK stars (null hypothesis rejection confidence level of only 91.7%). Noting also that the young disk stars have ages comparable to or younger than the Hyades ages, we are led to suggest that the difference in $\langle \log (L_x)\rangle$ for the two samples can in part be attributed to a sensitivity effect: the Hyades upper limits in X-ray luminosity are higher than those of the young field star survey (due to greater Hyades distance). Such an explanation is not viable in the case of the old disk stars because the reduction in sensitivity that could explain the observed behavior would be too large to be compatible with

the typical exposure times of the Hyades survey. Moreover, since the characterization of a given field star as young or old disk is based upon statistical considerations of the space velocity components (U, V) (Upgren 1978), contamination of these two samples is possible and would have the effect of lowering the true $\langle \log (L_x)\rangle$ value for the young disk population stars and increasing the $\langle \log (L_x)\rangle$ value for the old disk population stars. This effect can partially account for the slightly lower value of $\langle \log (L_x)\rangle$ for the young K field stars with respect to that of the K Hyades members.

We note that the value of log (L_x) for the K stars in the Pleiades ranges between 29.77 and an upper bound of 29.20 (Micela *et al.* 1985), while the corresponding range for the Hyades is from 29.20 to 28.35. Applying the Wilcoxon test to the K star distributions of the Hyades and the Pleiades, we find them to be rather dissimilar (rejection of the null hypothesis that the two samples are drawn from the same parent population can be made with 99.8% confidence). We have also applied this test to K and solar type stars within the Hyades, and in this case there can be no doubt that these stars have different luminosity distributions (the analogous null hypothesis is rejected at a confidence level greater than 99.99%).

iv) *M Stars*

Due to the intrinsic faintness of M stars, the problem of the completeness of the optical Hyades catalog is more severe for these stars than for the K stars. Hence it is imperative that we test the color distribution of the Hyades M stars in our survey against that of the nearby M stars before we can perform any test on the X-ray properties of these different samples. The catalog of the field dM stars within 10 pc is known to be complete, while the inclusion of the known dM stars between 10 and 25 pc makes the optical catalog incomplete. Because the bias working to limit the completeness of the optical catalog of the field M stars with distances larger than 10 pc should also be present in the Hyades catalog, we have compared the color distribution of the field M stars within 25 pc to that of the M stars of the Hyades and found that these color distributions are extremely similar (null hypothesis rejection confidence level is 40%).[11]

Satisfied that the color distributions are not unduly biased, we have performed a comparison of the X-ray properties of the sample of the field M stars within 25 pc with the sample of the Hyades M stars. We have detected 14 out of a total of 46 M stars belonging to the Hyades; the highest X-ray detection has log $(L_x) = 29.20$. We note in passing that the Hyades cluster center-region survey (Stern *et al.* 1981) reported detection for 17 of 50 K and M stars with an upper limit to the median log $(L_x) \le 28.5$. Using both detections and upper bounds, we have computed the integral X-ray luminosity function, shown as the solid curve in Figure 8*d*, and the following mean values for log (L_x):

$$\langle \log (L_x)\rangle_{\text{Hyades}} = 28.54 \begin{array}{l} +0.05 \\ -0.05 \end{array}$$

$$\langle \log (L_x)\rangle_{\text{Yd}} = 28.02 \begin{array}{l} +0.08 \\ -0.09 \end{array}$$

$$\langle \log (L_x)\rangle_{\text{Od}} = 27.14 \begin{array}{l} +0.18 \\ -0.13 \end{array}.$$

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[11] We have also compared the color distribution of the field M stars within 10 pc to that of the M stars of the Hyades; the test permits us to reject the null hypothesis at the 96% level.

In Figure 8e we also show the integral X-ray luminosity functions for the old disk (*dotted curve*) and young disk (*dashed curve*) M stars (Bookbinder 1985). The old disk M star distribution differs from that of the Hyades M stars at a confidence level of 93.5%, while the luminosity function of the young disk M stars [log (age) < 8.8] is indistinguishable from that of the M stars of the Hyades (significance level ∼10%). Finally, we note that the sensitivity level of the X-ray surveys of the Pleiades cluster [log (L_x) ≈ 29.2; Caillault and Helfand 1985, Micela *et al.* 1985] makes the detection of M stars with X-ray luminosities in the range of those observed in the Hyades essentially impossible.

In order to study the variation of X-ray emission levels with spectral type for stars of the Hyades age, we present the data in Figure 9a (a scatterplot of X-ray emission L_x versus $B-V$), to which we have applied Lowess smoothing (cf. Cleveland 1979) but modified in order to take into account the upper bounds. The result of this robust exploratory statistical procedure is also shown in Figure 9a. The interpolation curve peaks at $B-V \approx 0.5$ and shows a slow decline for later spectral type stars. In order to obtain a feeling for the significance of this result, we have also drawn in a (*dashed*) curve of L_x based on the assumption that the X-ray surface flux ($\equiv L_x/(4\pi R^2)$, with R taken from Allen 1973) is constant; this curve is normalized to the mean X-ray luminosity of the Hyades G stars, and hence no attempt has been made to "best-fit" this curve—only its slope is of interest for the moment. Upon comparing these two curves, it appears that in the 0.6–1.2 range of $B-V$ the observed stars have a variation of total X-ray emission level compatible with what would be expected if the surface X-ray flux were constant, in the mean as a function of color. This statement can also be quantified: by fitting a power law of the

form $L_x \propto (B-V)^{-\alpha}$ to the data for $0.6 < B-V < 1.2$, we find that $\alpha = 1.1[+0.27 - 0.34]$ (where the errors are specified at the 67% confidence level); the behavior expected if the surface flux were constant as a function of spectral type ($\alpha = 0.5$) thus lies slightly above the 67% (1 σ) confidence level boundaries, i.e. the hypothesis that the surface X-ray flux in this spectral type range is constant is consistent with the data. In any case, we do find that the Hyades stars show a *decrease* of mean X-ray luminosity with decreasing mass along the main sequence, a rather similar behavior of X-ray emission with color as the field stars in the nearby sample (cf. Vaiana *et al.* 1981). A summary of our results for the dependence of X-ray emission on stellar age, separated for each distinct range of spectral type, is presented in Figure 9b: We find that the level of X-ray emission L_x is not only a function of stellar age τ, but that it is also a function of color, i.e., $L_x = L_x(\tau, B-V)$, as just discussed.

b) Giants

Four giants, of spectral type K0 III, are certain Hyades members, namely θ^1, γ, δ, and ϵ Tau. An extensive investigation of the properties of their ultraviolet emission has been reported by Baliunas, Hartmann, and Dupree (1983), who point out the striking differences in the chromospheric (and coronal) emission among these stars in spite of the fact that these stars are otherwise quite similar (their photospheric properties are essentially the same: any differences in photospheric temperature can be at most of order 200 K). Their rotational velocities are very low (the order of 3 km s^{-1} or less), and again quite similar (Gray and Endal 1982; Baliunas, Hartmann, and Dupree 1983). X-ray emission was detected from the three giants contained in the IPC images of the
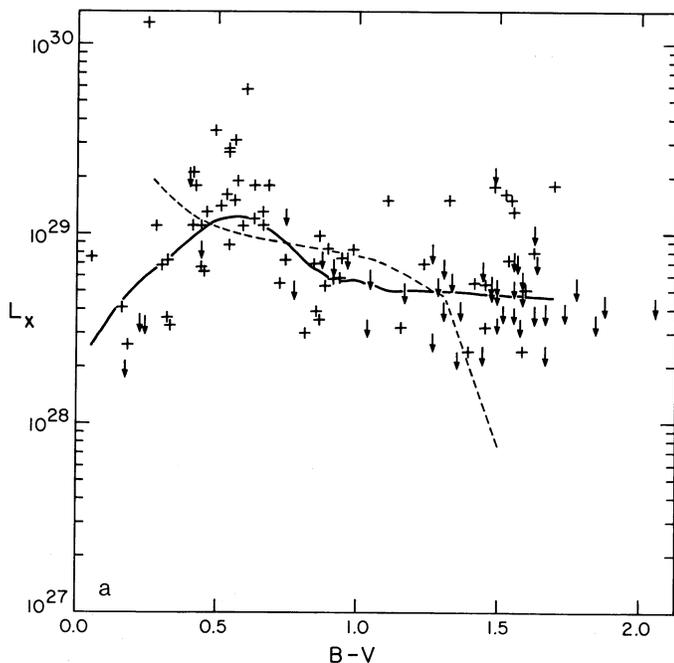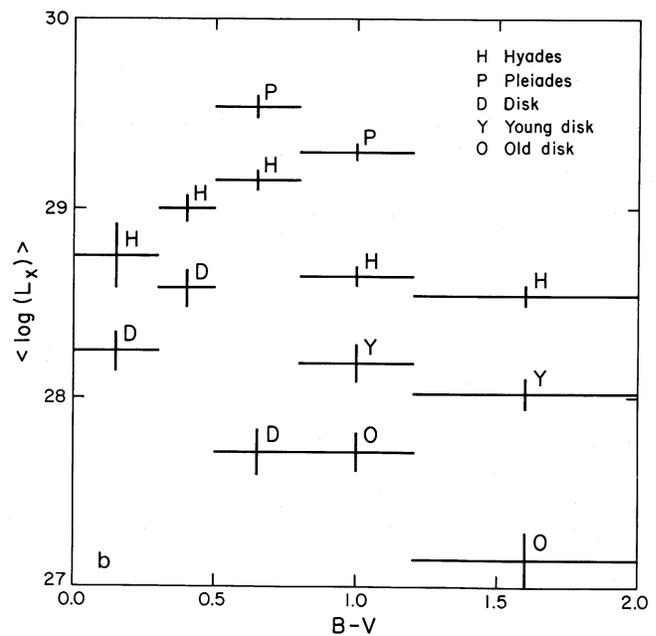

Fig. 9a

Fig. 9b

Fig. 9.—(a) Scatter plot of L_x vs. the color index $B-V$ for all the surveyed Hyades main-sequence stars. A slow dependence of L_x on $B-V$ is suggested by the data, as indicated by a modified Lowess fit (see text; *solid line*) to the X-ray data (including upper bounds), and as borne out by a more quantitative estimate of the slope of a power-law fit to the data for $0.6 < B-V < 1.2$; the behavior of L_x (see text; *dashed line*) based on the assumption that the X-ray surface flux ($\equiv L_x/(4\pi R^2)$, with R taken from Allen 1973) is constant is drawn for comparison; (b) summary of the behavior of $\langle \log(L_x)\rangle$ as function of spectral type and stellar age, as deduced from the volume-limited samples of nearby stars, and analysis of samples of coeval stars (including the present Hyades survey).

present survey, namely θ^1, γ, and δ Tau, and was also reported in the survey of the central region of the cluster (Stern *et al.* 1981). These stars are all spectroscopic binaries with long period but are quite different from RS CVn's (Baliunas, Hartmann, and Dupree 1983). Because their X-ray emission is too intense to be compatible with the emission from a typical late-type dwarf belonging to the Hyades, the hypothesis that the observed X-ray luminosity is due to a companion, such as the resolved G0 V–G5 V companion of θ^1 Tau (Peterson *et al.* 1981), is not easily justified. Moreover, the chromospheric observations of Baliunas and collaborators show that the giants are the probable source of the ultraviolet emission. On the basis of these considerations, we will assume in the following that the giants themselves are X-ray emitters.

Due to the large uncertainties in distance determinations (up to a factor of 2) for these three giants, we prefer to use the distance-independent measure f_x/f_v in order to compare their X-ray emission properties. Because these stars are photospherically similar, we feel confident in this procedure. The mean values of this ratio are

$$(f_x/f_v)_{\theta 1} = 3.17(\pm 0.12) \times 10^{-5}$$

$$(f_x/f_v)_{\gamma} = 1.31(\pm 0.10) \times 10^{-5}$$

$$(f_x/f_v)_{\delta} = 4.61(\pm 0.11) \times 10^{-6}$$

We conclude, in agreement with the results of Baliunas and collaborators, that θ^1 and γ Tau are more active than δ Tau.

In an attempt to clarify the reason(s) for these differences in X-ray emission, we have searched for long-term variations in the X-ray emission levels of these three giants. As reported by Zolcinski *et al.* (1987), γ Tau has been observed twice, with a time separation of the order of some hours, and does not show evidence of variability on this time scale. The star δ Tau has been observed twice, with a time separation of the order of months; it is constant (within 1 σ). The star θ^1 has been observed three times, on time scales ranging from months to a year, and its flux level is also constant, the constancy of the X-ray flux from this giant was previously discussed (Stern and Zolcinski 1982; Zolcinski and Stern 1985). These results, although inconclusive due to the paucity and the quality of the data, do not support the suggestion of Baliunas and collaborators that the large spread in the emission levels of these stars is due to the presence of cyclic variability.

c) *White Dwarfs*

In the present survey only three of the 11 confirmed Hyades white dwarfs (Eggen 1969), namely EG 36, EG 37, and EG 38 were observed. (In the earlier survey of the central Hyades region [Stern *et al.* 1981], two of these three white dwarfs were included but neither was detected.) The first two were observed twice, but not detected; the computed upper bounds range between 4 and 7 $\times$ 10^{29} ergs s^{-1}. The star EG 38 was observed three times and detected once at a level of $L_x = 3.3 \times 10^{29}$ ergs s^{-1}; its two upper limits are compatible with the detection. However, this star probably has an unresolved dM companion (Eggen and Greenstein 1965a, b) that could well be responsible for the observed emission. This is further substantiated by the fact that the X-ray luminosity inferred from this detection is compatible with the results of Vaiana *et al.* (1981) and of Fontaine, Montmerle, and Michaud (1982), who surveyed a sample of white dwarfs and report values of, or upper limits to, log (L_x) ranging between 26.5 and 28.9.

d) *Correlation with Rotation for Solar-like Stars*

Correlations between X-ray emission and rotation rate have previously been investigated by, for example, Pallavicini *et al.* (1981, 1982), and Walter (1981, 1982) and the various correlations found have been interpreted as evidence for solar-type magnetic field related phenomena on other stars. However, most previous studies have made use of stars differing, not only from the point of view of rotational velocities, but also in terms of ages, i.e., the space of the parameters involved was larger than explicitly assumed. Moreover, there is evidence that the Pleiades K stars (Caillault and Helfand 1985; Micela *et al.* 1985) do not follow the quadratic law found by Pallavicini *et al.* (1981), who considered stars in the spectral range F7 to M5, and whose results were confirmed by Maggio *et al.* (1987) in a study of nearby solar-like stars.

The Hyades sample of the solar-like stars is quite homogeneous because all stars have approximately the same age (thus reducing the dimensionality of the parameter space). Moreover, according to Benz, Mayor, and Mermilliod (1984) the velocity distribution of the Hyades stars in the range F5–K3 is, at a given color, consistent with a Dirac δ-function; this is expected for coeval stars if the rotation rate is determined only by age. A relation between L_x and $v \sin i$ would then predict that all stars in this sample have the same activity level. In the previous Hyades cluster survey limited to the central region, Stern *et al.* (1981) discussed the relation between L_x and the average equatorial rotation velocity, v_e, concluding that the average X-ray luminosity for the Hyades G stars they detected was consistent with a quadratic dependence of L_x on v_e.

Figure 10 shows the scatter plot of log (L_x) versus log $(v \sin i)$ for the subsample of solar-like stars for which both X-ray luminosity and rotation rate are known (17 stars); upper limits in one parameter or the other are indicated with arrows. We also show the relation deduced by Maggio *et al.* (1987), who considered a sample of the nearby (i.e., $d < 25$ pc) solar-
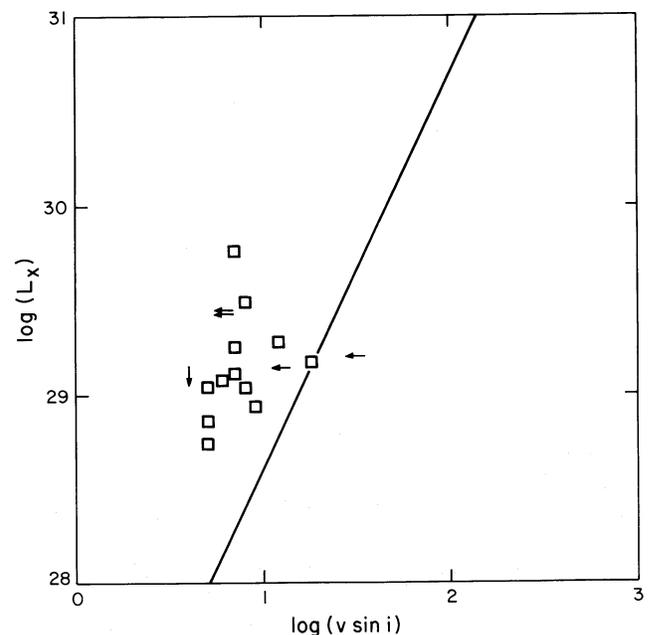

Fig. 10.—Scatter plot of log (L_x) versus log $(v \sin i)$ for the Hyades solar-like stars. Overlaid is the relation deduced by Maggio *et al.* (1987) from analysis of a volume-limited sample of nearby solar-like stars.

like stars. The spread in $v \sin i$ (less than one order of magnitude) can be explained in terms of random orientation of the rotational axes (Benz, Mayor, and Mermilliod 1984), but neither the observed spread in the X-ray luminosity (about one order of magnitude) nor variations in other properties of these stars can be explained by comparable statistical errors in the measurements. For example, the mass of these stars cannot be responsible for the spread in X-ray emission because the range of masses in the spectral range F7 to K0 is quite small (less than a factor 2), so that the dependence of L_x on $B-V$ would have to be very steep in order to take into account the observed spread in L_x. Furthermore, Maggio *et al.* (1987) recently demonstrated that in a restricted $B-V$ range there is no strong dependence of L_x on $(B-V)$. Multiplicity can only partially account for the observed spread (say, approximately a factor of 2). Another explanation would be long- and short-term variability of the X-ray emission, but evidence for variability has been demonstrated only for a couple of the solar-like Hyades stars (Zolcinski *et al.* 1987).

VI. CONCLUSIONS

We have investigated coronal X-ray emission from coeval members of the Hyades stellar open cluster and have computed maximum likelihood integral X-ray luminosity functions for the Hyades stars for given color index ($B-V$) ranges. An overall comparison of the results of the present survey with those of a previous survey of the central region of the cluster (Stern *et al.* 1981) shows a good agreement in both qualitative and quantitative results, notwithstanding the facts that the earlier survey was limited to only 27 out of the 63 fields analyzed in the present survey, that we have used the final version of IPC data processing system, and that we have made extensive use of sophisticated statistical analysis techniques which were unavailable for the previous work. Thus we find substantial agreement with the conclusion of the previous survey among the ubiquity of the stellar activity in the Hyades cluster, in particular among solar-type stars.

Our analysis of the X-ray emission from the 121 Hyades members studied in the present survey allows us to draw the following major conclusions.

a. We confirm the earlier result of Stern *et al.* (1981) that stellar X-ray emission is dependent on stellar age: X-ray emission for the young solar-like Hyades stars is more intense than that for nearby, generally older, solar-like stars. We also show that the X-ray luminosity distribution functions of the K and M stars of the Hyades are consistent with those of the nearby young disk K and M stars, while the nearby old disk K and M stars have much smaller levels of X-ray emission than those of the corresponding sources of the Hyades.

b. In addition, we show that the X-ray luminosity L_x is not only a function of stellar age τ, but is also a function of color, i.e., $L_x = L_x(\tau, B-V)$.

c. We confirm that the Hyades A stars are quite similar to a sample of nearby A stars, with the exception of the star 71 Tau, which is a δ Scuti variable with a wide G4 V companion and has an unusually high and anomalous X-ray emission level.

d. We confirm that θ^1 and γ Tau are more active than δ Tau by comparing the values of f_x/f_v for the three Hyades giants present in this survey.

e. We show that an excess of X-ray–detected, solar-like, field stars can be explained as arising from Hyades stars whose membership has not been properly assessed: X-ray emission can therefore be used as a criterion for cluster membership. With the exception of solar-like stars, the number of detected field stars is consistent with our knowledge of their X-ray luminosity functions and spatial distribution in our Galaxy.

APPENDIX A

COUNT RATE DETERMINATION

The standard REV-1 processing system (Harnden *et al.* 1984) computes count rates for the detected sources by correcting the raw count rates for the effects of mirror vignetting, detector spatial response, and shadowing by the IPC entrance aperture edges and support structure (ribs). It employs two distinct algorithms to detect X-ray sources: *Local* detect, in which the background is estimated directly from the image in the immediate vicinity of the detected source, and *Map* detect in which comparison with a background reference map (properly scaled to the given image) is used to establish the existence of sources in the observed image. The Local method, which is used on all fields, is somewhat less sensitive than the Map method; but in order to prevent spurious Map detections in the vicinity of strong sources or diffuse emission, the Map algorithm is not run on some of the fields. In the present survey, the Map method was run for 56 of 63 fields, and we obtained 318 detections: 275 Map detections and 180 Local detections, with 137 detections common to both methods.

In principle, the two detection methods may yield different count rate determinations for the same source, thus producing possible inconsistencies. We have investigated to what extent we can freely interchange count rates derived with these two methods for our survey sources. For this purpose we have derived the distribution of the ratio of Local-computed to Map-computed count rates for all sources detected with both methods. This distribution, shown in Figure 11, has a mean of 0.95, with a standard deviation of 0.20, and demonstrates that the two methods give a consistent count rate evaluation *within the statistical errors*. The distribution is consistent with a Gaussian, suggesting that the dispersion of points can be explained in terms of randomly distributed errors in individual measurements.

Further problems arise when the X-ray sources are detected near the IPC edges or ribs; in this case, the determination of the true source count rate is in principle subject to systematic underestimation. In our sample, about half of the sources are affected by such shadowing.

The Local algorithm uses a detection cell subdivided into nine central subcells (3×3) with a background frame (around the central cell) subdivided in 16 subcells. The RECO (Ribs and Edge shadowing COde) value provides an estimate of the number of background and detection subcells potentially obscured and is nonzero whenever a source could have any of its central or frame subcells obscured. However, this approach necessarily employs simplifying assumptions regarding the shape and dimensions of the ribs, and it neglects spectral dependencies (cf. Harnden *et al.* 1984). Consequently, although a quantitative attempt is made to correct for such effects using the RECO values, the only completely reliable approach is to regard count rates for sources with nonzero RECO values as indeterminate. Note that the Map algorithm misses fewer detections near the edges or the ribs because its background is derived from a map and is not evaluated in the local image framework.

To investigate whether the two methods give consistent results in the presence of aperture shadowing, we have constructed distributions of count-rate ratios (Local/Map). A comparison of the distribution for all sources (Fig. 11) with that for the potentially obscured sources (Fig. 12) shows that they are virtually indistinguishable and demonstrates that the count rates are not systematically affected by a nonzero RECO code. However, this result does not prove that count rates derived in the vicinity of aperture obstructions can be used freely with those derived for sources unaffected by ribs or edges.

Pursuing this problem further, we have considered sources observed more than once with different RECO values; however, we have excluded sources that may be variable (cf. Zolcinski *et al.* 1987). In order to estimate the intrinsic scatter of the count rates due only to statistical errors, we have considered those sources observed more than once with no shadowing; 44 measurements meet this requirement. Using these sources, we have computed the cumulative distribution of the ratio of observed to "true" flux, where the "true" flux is taken to be the mean value (cf. Fig. 13, *solid line*). The mean value of the ratio is 0.995 ± 0.10, in agreement with the expectation, while the intrinsic dispersion of data points, as measured by their standard deviation, is less than or equal to 0.20.

In addition, we have considered those sources with at least one observation without possible shadowing and with one or more potentially obscured observation; 47 measurements meet this requirement. For these sources, the cumulative distribution of the ratio of count rate determined with nonzero RECO to that determined with RECO = 0 is shown in Figure 13 (*dashed line*). The mean value is 0.998 ± 0.09, and the intrinsic dispersion of data is ~ 0.50. From these results we conclude that potential shadowing does not introduce a systematic shift in the count rate estimation but does introduce a greater random error. The greater dispersion is simply due to poorer counting statistics, since high RECO implies the utilization of fewer counts (potentially shadowed subcells are not used) and hence greater statistical error. To verify this hypothesis we have compared the cumulative distributions of the statistical errors for the two samples. The resulting mean statistical error is $\sim 20\%$ in the RECO = 0 sample and $\sim 40\%$ in the other sample; on the other hand, we have computed a value of 50% for the dispersion of the distribution of RECO different from 0 (mean statistical error 40%) versus RECO 0 values (mean statistical error 20%), i.e., the value of 50% for the data dispersion can be accounted for by the intrinsic dispersion of the considered samples.

In summary we conclude that proximity to ribs or edges does not systematically change the statistical properties of an ensemble of sources, although it does increase individual measurement errors. In 98% of the cases we have examined such errors were less than or equal to a factor of 2. Although this result contradicts the naive expectation that potentially obscured-source fluxes would be systematically underestimated, it can be argued that the dimensions of the window support structure were too conservatively
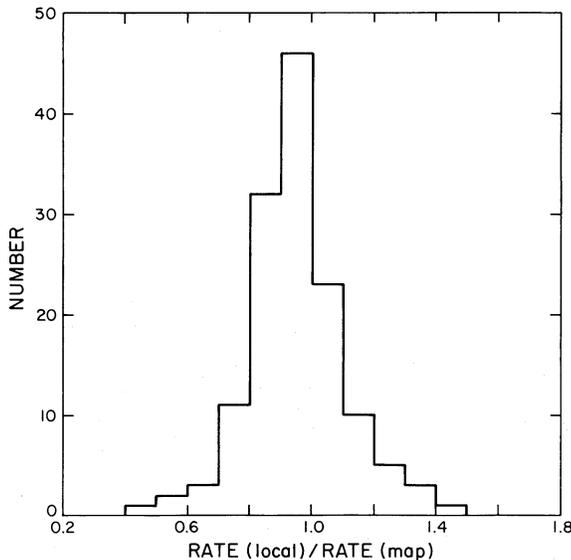

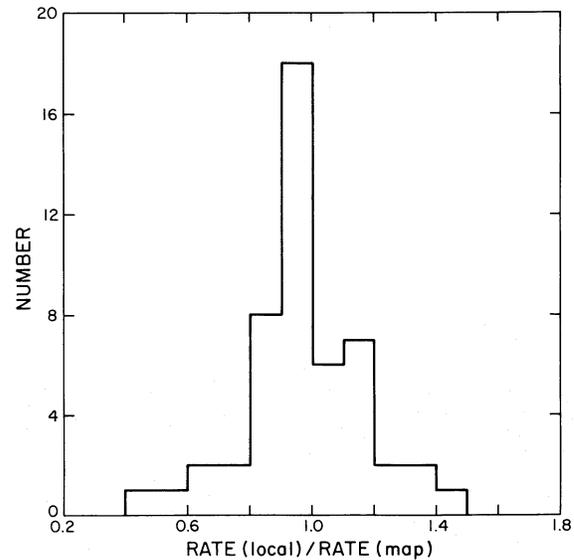FIG. 11   FIG. 12

FIG. 11.—Differential distribution of the ratios of *Local* and *Map* computed count rates for all the X-ray sources detected with both methods.
FIG. 12.—Differential distribution of the ratios of the *Local* and *Map* computed count rates for all the X-ray sources potentially obscured by the ribs or the edges (i.e., RECO $\neq$ 0).
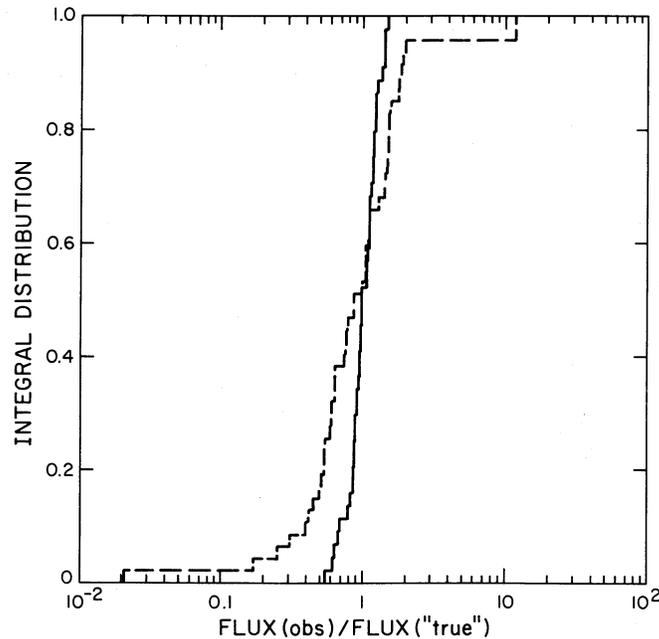
Fig. 13.—Integral distribution for X-ray sources observed more than once, with RECO = 0 in each observation, as a function of the ratio of the individual count rate measurement to the mean count rate value for the given source (*solid line*), and the integral distribution of the Hyades X-ray sources observed more than once with only one observation with RECO = 0 as function of the ratio of the nonzero RECO count rate measurement to the RECO = 0 measurement (*dashed line*).

overestimated by the data reduction software and that in practice only a very few sources will fall near enough to the actual support structure to have their observed fluxes substantially underestimated. In the sample considered here, which is perhaps the sample best suited for detecting such an effect, we discern no significant effect.

Therefore, we have adopted the following procedure to compute source count rates:

a. For detections, we take a weighted (by inverse square of statistical error), mean count rate of all observations with RECO = 0. If there are no unobscured observations for a source, then RECO $\neq$ 0 measurements are used.

b. For upper bounds, we use the lowest, available value measured with RECO = 0. If only RECO $\neq$ 0 values are available, we conservatively retain the largest such value.

APPENDIX B

DETECTOR SPATIAL-RESPONSE CORRECTION

Because of the size of the IPC point response function, we expect that a certain number of stellar X-ray counts will fall outside the broad detection cell. To correct for this effect we have considered the count rates measured in a circle of radius 3'. (This radius is large enough to collect almost all counts from a point source; we have also corrected for the presence of other sources nearer than 6'.) In the following we will deal only with sources identified with Hyades stars and with RECO = 0; 40 sources meet these requirements.

We have constructed the distribution of the ratio of count rate measured in the circle to the count rate measured with the Map method. This distribution is shown in Figure 14. The two low points are due to two sources whose distance from the ribs is such that the ribs partially obscure the circle, but do not obscure the detection cell, affecting the count rate in the circle and not affecting the cell count rate. At the other extreme, the higher values are generally obtained for sources with nearby, unresolved emission that is inadvertently included as intrinsic emission of the source. However, the mean value and the standard deviation of this distribution are not strongly affected by the presence of these high values; because of the difficulty of screening the sources with nearby fluctuations, we compute the mean value using all sources except the two near the ribs. The resulting mean value is 1.25, with a standard deviation of 0.20.

To correct the count rates for these spatial response effects, we adopted the following procedure:

1. For the 40 sources detected both with Map and Local methods, excluding the two sources in which the rates in the circle are in disagreement with the Map count rates, we use the circle count rate value.

2. For the two sources discarded under (1) and for the 13 sources only Map detected we use the Map count rate multiplied by the mean correction factor 1.25 obtained previously.

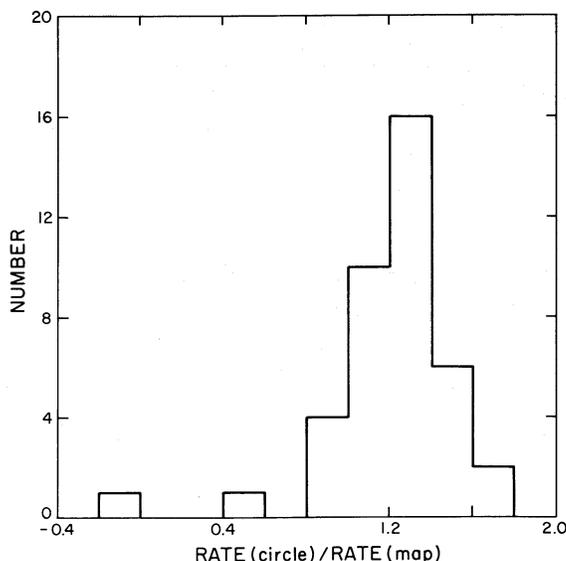3. For the four sources only Local detected we use the circle count rate.

Fig. 14.—Differential distribution of the ratio of circle-evaluated count rates to cell-evaluated (*Map*) count rates for the sample of the 40 X-ray sources identified with Hyades stars and not affected by rib or edge shadowing.

4. For the sources detected only with RECO $\neq 0$ we use the Map value corrected by the factor of 1.25.

5. For the upper limits we use always the Local cell value corrected by a factor 1.25.

We estimate that the resulting maximum error is $\sim 30\%$, which follows from the width of the distribution of the ratio of 3' circle to detection-cell rates.

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