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EINSTEIN X-RAY SURVEY OF THE PLEIADES: THE DEPENDENCE OF X-RAY EMISSION ON STELLAR AGE

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ABSTRACT

Two 1° × 1° fields of the Pleiades region, containing 78 cluster members within a limiting magnitude of 14 mag and centered on two of the most luminous stars of the cluster (20 Tau and 17 Tau) have been observed with the *Einstein* (*HEAO 2*) *Observatory* imaging proportional counter. The exposure times (~ 3–4×10^3 s) and background level give, at the Pleiades distance (~ 127 pc), a mean detection threshold of $10^{29.5}$ ergs s^{-1}. We have detected one (out of eight) B stars, one (out of 13) A stars, two (out of 10) F stars, 11 (out of 21) G stars and six (out of more than 26) K stars. The brightest X-ray source is Hz II 253 (G1), with $L_x \approx 10^{30.3}$ ergs s^{-1}.

We derive the maximum-likelihood X-ray luminosity functions for the G and K stars in the cluster, and show that for the G stars, the Pleiades X-ray luminosity function is significantly brighter than the corresponding function for Hyades G dwarf stars. The significantly larger number of X-ray bright G stars than K stars (even though the Pleiades K stars appear to be relatively rapid rotators), and the lack of detection of M stars, suggest that the connection between stellar rotation and the level of X-ray emission is not as straightforward as has been heretofore thought.

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

I. INTRODUCTION

One of the most striking features of stellar X-ray emission discovered with the *Einstein* (*HEAO-2*) *Observatory* is the fact that stars of the same spectral type and luminosity class emit over a wide range. Since the internal structure and the photosphere of stars of a given spectral type and luminosity class are similar, the range of X-ray emission observed can only be explained by relating it to other physical stellar parameters which do not traditionally figure in placing stars in the H-R diagram.

For example Pallavicini *et al.* (1981, 1982); see also Walter (1981), have investigated the dependence of X-ray luminosity on stellar rotation rates for a large sample of X-ray sources, and have found that most of the variance in the emission levels of stars for spectral types later than F7 can be related to the observed dispersion in rotation rates. Thus they find that the X-ray luminosity is quadratically related to the stellar rotation rate or, more specifically, that $L_x \approx (v \sin i)^{2.0}$, where L_x is the X-ray luminosity and $v \sin i$ is the equatorial rotation speed projected along the line of sight. This result can be understood qualitatively by assuming that the mechanism responsible for heating the outer atmosphere of late-type stars to temperatures of several million K is related to dissipation of energy in magnetic-field–dominated regions at the stellar surface. The stellar rotation therefore enters in the above relation because in stellar dynamo theory it is one of the important parameters which determine the rate of magnetic-field generation in the stellar interior. Similar arguments can be made regarding the observed correlation between stellar activity indicators and Rossby number (cf., Noyes *et al.* 1984; Schmitt *et al.* 1985; Micela, Sciortino, and Serio 1984; Serio 1984).

Since stars lose their angular momentum in the course of their evolution, it is also reasonable to investigate the dependence of X-ray luminosity on stellar age. Stern *et al.* (1981) have in fact surveyed the Hyades open cluster, which has an age of $\sim 6 \times 10^8$ yr, and have found that the median X-ray luminosity (L_x) of G stars in this cluster is ~ 30 times larger than that of the Sun, consistent with a quadratic dependence of L_x on stellar age. In contrast, Ku and Chanan (1979). Feigelson and De Campli (1981), and Montmerle *et al.* (1983) have observed pre–main-sequence G stars in regions of recent star formation, whose median X-ray luminosity ($\sim 10^{31}$ ergs s^{-1}) suggests a linear decay of L_x with stellar age; a similar result was obtained by Micela *et al.* (1983) from preliminary analysis of X-ray observations of stars in the Pleiades. This paper addresses the question of the stellar activity–age relation by examining the complete results of an *Einstein* X-ray survey of the central region of the Pleiades, a well-known galactic open cluster somewhat younger than the Hyades.

Our paper is organized as follows: we describe the data selection procedures, the method of analysis, and the results of the survey in the next section. The implications of these results for the dependence of X-ray emission from late type stars on the properties of the underlying star are discussed in § III. Our results are summarized in § IV.

II. DATA SELECTION, METHOD OF ANALYSIS, AND RESULTS

Two *Einstein* IPC (Gorenstein, Harnden, and Fabricant 1981; Giacconi *et al.* 1979) exposures centered on two of the brightest stars of the Pleiades (17 Tau and 20 Tau) were obtained on 1981 February 7 and 8. The two fields overlap by

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TABLE 1

CHARACTERISTICS OF THE OBSERVATIONS

	I-5457	I-5458
Center coordinates (α, δ)	$3^h41^m54^s.1$	$3^h42^m50^s.8$
	$23°57'27''.8$	$24°12'46''.9$
Start time (JD)	2142.8131	2143.9195
Effective exposure (s)	2931.0	4734.4
Cluster stars ($m_v < 14$)	57	61
Limiting sensitivity	$\sim 2.8 \times 10^{29}$ ergs s^{-1}	$\sim 2.3 \times 10^{29}$ ergs s^{-1}

approximately 50% in the $\sim 60' \times 60'$ useful region of the IPC field of view, and consequently 40 Pleiades stars fell into the overlap region. The characteristics of the two exposures are summarized in Table 1, while Table 2 lists those stars which are included in the field of view of the two exposures which are part of the cluster according to the Hertzsprung catalog (1947, hereafter Hz II). At the distance of the Pleiades, this catalog's completeness limit of apparent magnitude 14 corresponds to spectral type late K.

a) *Analysis Procedures*

The data have been analyzed by means of the revised *Einstein* IPC software (Harnden *et al.* 1984).[2] Images were searched for 3 σ fluctuations with respect to the local background in the energy band 0.2–3.5 keV. Vignetting, detection-cell extension, and shadowing by the IPC entrance aperture ribs were taken into account to give the effective count rate for each detected source together with its statistical error. With the detection threshold at 3 σ, approximately two of the sources are expected to be spurious. The positions of the detected X-ray sources were compared with the positions of all the stars (with $m_v < 14$) falling in the useful field of view. We have used as identification criterion the condition that the position of the X-ray source be within 1' of the position of the optical star. This procedure gives a probability of chance identification with cluster members of less than 5×10^{-3}.

In addition to searching for X-ray sources in the field, we have also obtained count rates (corrected for instrumental effects as above) at the locations of all cluster stars in our catalog. Table 3 summarizes our results: We provide luminosities for all stars detected above the 3 σ level; call out all stars for which the detection significance level lies between 2 σ and 3 σ, and give the corresponding luminosities; and provide 2 σ upper bounds for the remaining stars. Random fluctuations are expected to occur in $\sim 2\%$ of the trials in composing such a list; hence, about two false sources appear in the 2 σ portion of Table 3, for a total of perhaps four false sources in Table 3.[3]

We have converted from count rates to X-ray luminosities using a conversion factor of 2.2×10^{-11} ergs count^{-1} cm^{-2}. This value was obtained by assuming a source temperature of $\sim 3 \times 10^6$ K and a hydrogen column density of 2.0×10^{20} cm^{-2}; the latter was computed according to Bohlin, Savage, and Drake (1978) using a reddening of $E(B-V) \approx 0.04$ (Crawford and Perry (1976). The total conversion factor for count rate to luminosity, assuming a common distance of 127 pc for all cluster members, is then 4.35×10^{31} ergs count^{-1}.

b) *Results*

We show a map of the region surveyed, giving the locations of both the Pleiades stars in the two fields and the detected sources, in Figure 1. The inferred X-ray luminosity along with its statistical uncertainty, or the 2 σ upper limit, are listed in Table 3 for all stars in our catalog, as explained above. The errors listed in Table 3 are the statistical errors. The estimated overall error in the X-ray luminosities is $\sim 40\%$–60%; it consists of statistical errors (ranging from 15% to 50%), systematic errors in instrument calibrations ($\leq 20\%$; Harnden *et al.* 1979), errors in the individual cluster member distance ($<3\%$), and systematic errors in converting counts to flux due to the assumed hydrogen column density and source temperature ($\leq 20\%$).

We have detected a total of 21 distinct X-ray sources, associated with cluster members, 14 of which are significant at above the 3 σ level and 7 at above the 2 σ level. More specifically we have detected: one (1 + 0) out of eight B stars; one (1 + 0) out of 13 A stars; two (1 + 1) out of 10 F stars, 11 (11 + 0) out of 21 G stars; and six (1 + 5) out of 26 K stars in the Hz catalog (since the Hz catalog is not complete for apparent magnitudes greater than 14, this corresponds to an upper limit on the fraction of K stars detected).

Three additional X-ray sources detected at the 3 σ level do not correspond to any catalogued Pleiades star within a distance of 1' from the detection-cell center. Two of these X-ray sources have been identified with field stars using the same identification criterion as discussed above; the remaining star may well correspond to an uncatalogued late K or M star.

Our results are summarized in graphical form in Figures 2–4. Figure 2 shows an H-R diagram of the cluster stars in the two fields of view for which count rates were obtained. The statistics of the breakdown into spectral types of the detected stars is given in Figure 3; Figure 4 summarizes the inferred X-ray luminosities and upper limits obtained in this survey. As can be seen from Figure 3, we have values for the X-ray luminosity for more than 50% of the G stars in our sample; hence the median of the X-ray luminosity function for G stars in the Pleiades can be estimated from Figure 4 as the luminosity of the weakest X-ray source identified with a G star: L_x (median) = $10^{29.5}$ ergs s^{-1}.

III. DISCUSSION

In this section we discuss the conclusions which can be drawn from our survey, with particular attention to the dependence of the level of stellar X-ray emission on age.

a) *Comparison with Other Surveys*

It is particularly useful to compare the data presented here with the results of the *Einstein* Hyades survey (Stern *et al.*

[2] One of the important differences between this revised software and the former version is in the source-detection algorithm, which searches for fluctuations with respect to the *local* background rather than with respect to an *average* background. This ensures more reliable results for sources near the detection threshold, as well as in crowded fields.

[3] The results of a survey of the same region reported by Caillault and Helfand 1985 are not directly comparable to ours for the marginally detected sources, since they used the earlier "Rev O" *Einstein* software.

1985ApJ...292..172M

TABLE 2

PLEIADES STARS IN THIS SURVEY

Hz II	R.A. (1950)	Decl. (1950)	m_v	Ref.	$B-V$	Sp.[a]	Ref.	V_r[b]	Ref.	P[c]	Notes
120	$3^h40^m34^s.1$	23°31′03″	10.79	1	0.70	F6		...		...	
158[d]	3 40 44.5	24 13 06	8.23	1	0.25	A7	2	70	3	...	
193[d]	3 40 52.2	24 05 29	11.29	1	0.81	G7		...		0.97	
232	3 41 01.3	24 24 04	8.06	1	0.20	A5	2	20	3	...	HD 23194
233	3 41 00.7	23 43 37	9.66	1	0.52	F7		80	3	...	
253	3 41 04.6	24 20 54	10.66	1	0.68	G1	4	...		...	
263[d]	3 41 06.2	24 07 10	11.54	1	0.88	G8	4	...		0.98	
298[d] 299[d]	3 41 14.4 3 41 14.7	23 52 34 23 52 30	10.86	1	0.88	G + K		...		...	e
303[d]	3 41 16.2	23 56 47	10.48	1	0.89	G9		...		...	
314	3 41 20.8	24 38 26	10.56	1	0.64	G1	4	...		...	
320	3 41 21.2	24 37 02	11.04	1	0.88	G5	4	...		...	
324	3 41 22.6	24 36 46	13.00	5	1.07	K2		90		...	
335[d]	3 41 24.6	23 54 46	13.76	5	1.28	K5	6	...		0.56	f
338	3 41 25.1	23 58 37	9.07	1	0.46	F2	2	<40	3	...	
344[d]	3 41 26.9	24 14 21	8.17	1	0.27	A8	2	200	3	...	
345[d]	3 41 27.2	24 26 03	11.65	5	0.85	G8	4	...		0.99	
357	3 41 29.4	24 00 58	13.32	7	1.19	K6	6	<10		0.99	f
405	3 41 41.5	24 39 47	9.83	1	0.54	F9	2	15	8	...	
430[d]	3 41 45.3	24 04 33	11.45	5	0.85	G8	4	...		0.99	
447[d]	3 41 49.5	24 08 04	5.46	1	−0.04	B7 IV	2	260	3	...	16 Tau
468[d]	3 41 54.0	23 57 29	3.71	1	−0.11	B6 III	2	220	3	...	17 Tau
476[d]	3 41 55.6	23 45 58	10.81	1	0.80	G1	4	...		...	
489[d]	3 41 57.6	24 16 39	10.36	1	0.63	G0	2, 4	...		...	
522[d]	3 42 05.1	23 41 05	11.97	5	0.92	K2	9	...		0.99	
530	3 42 07.2	23 32 52	8.95	1	0.39	F3		<40	3	...	
531[d]	3 42 07.9	24 06 31	8.58	1	0.31	Am?	2	75	3	...	
541	3 42 10.4	24 41 03	5.65	1	−0.07	B8	2	245	3	...	HD 23324
554[d]	3 42 12.9	24 25 53	14.09	9	0.92	K5	9	...		0.94	
563	3 42 13.5	24 18 45	4.31	1	−0.11	B6	2	135	3	...	19 Tau
625	3 42 23.1	23 34 23	12.57	1	1.10	K3		>50		0.96	g
652	3 42 27.7	23 52 50	8.04	1	0.21	A3	2	235	3	...	
676	3 42 31.4	23 36 21	13.71	5	1.31	K3.5	6	<10		0.99	f
686[d]	3 42 34.2	24 08 56	13.62	1	1.04	K2		150		0.99	f, g
697[d]	3 42 35.5	24 18 32	8.60	1	0.35	A9	2	75	3	...	
708[d]	3 42 36.9	23 55 44	10.13	1	0.62	G0	4	70	8	...	
717[d]	3 42 39.0	24 10 53	7.18	1	0.16	A1	2	15	3	...	HD 23387
727	3 42 41.1	24 28 23	9.70	1	0.55	F9	2	45	8	...	
738	3 42 41.3	23 35 60	12.26	1	1.16	G5	10	>60		0.93	
745[d]	3 42 42.7	24 08 03	9.45	1	0.52	F5	2	65	8	...	
746[d]	3 42 42.9	24 16 38	11.27	1	0.92	G5	4	...		0.99	
761[d]	3 42 45.7	24 03 58	10.55	1	0.67	G1	4	...		...	
785[d]	3 42 50.8	24 12 49	3.88	1	−0.07	B7 III	2	40	3	...	20 Tau
793[d]	3 42 50.7	23 41 56	14.305	5	1.40	K8		<10		0.96	f
799[d]	3 42 52.2	23 43 12	13.71	5	1.31	K3	10	<10		0.96	
804	3 42 53.2	23 53 05	7.85	1	0.20	A2	2	170	3	...	
817	3 42 55.4	24 24 02	5.76	1	−0.04	B8	2	220	3	...	21 Tau
859	3 43 03.9	24 22 26	6.43	1	−0.02	B9	2	250	3	...	22 Tau
870	3 43 04.7	23 35 00	12.72	1	1.24	K5		...		0.93	
879[d]	3 43 07.4	24 24 49	12.82	5	1.08	K2		<10		0.96	e, g
883[d]	3 43 07.8	24 24 33	13.05	5	1.15	K4		...		0.99	e, f
885	3 43 08.3	24 42 47	12.05	1	1.01	K3	4	<10		0.97	
916[d]	3 43 12.6	24 28 07	11.71	1	0.87	G8	4	...		0.99	
956[d]	3 43 17.3	24 02 10	7.96	1	0.32	F0		150	3	...	HD 23479
974	3 43 21.1	24 37 55	13.86	5	1.32	K7	9	...		0.95	
980	3 43 21.1	23 47 41	4.18	1	−0.06	B6 IV	2	275	3	...	23 Tau
996[d]	3 43 23.5	24 25 00	10.42	1	0.64	G1	4	...		...	
1028[d]	3 43 28.5	24 06 06	7.35	1	0.10	A2	2	110	3	...	
1032[d]	3 43 29.4	24 16 50	11.34	1	0.86	G8	4	...		0.99	
1061[d]	3 43 32.5	23 57 49	14.28	5	1.42	K5	10	<10		0.95	f
1094[d]	3 43 37.5	23 48 49	14.02	1	1.40	K8		...		0.91	e, f
1100[d]	3 43 38.4	24 11 24	12.16	1	1.15	K3	4	<10		0.92	f
1110[d]	3 43 39.8	24 22 01	13.41	9	1.23	K6.5	6	...		0.99	
1117	3 43 39.5	23 38 04	10.20	1	0.73	G6	2	...		...	
1122	3 43 40.7	23 56 60	9.29	1	0.46	F4	2	28	8	...	
1124[d]	3 43 40.8	23 52 35	12.12	1	0.92	K0	4	<10		0.97	g
1207	3 43 55.4	24 38 36	10.47	1	0.62	G1	4	...		...	
1266	3 44 04.1	24 40 01	8,28	1	0.36	F2		95	3	...	HD 23567
1280[d]	3 44 04.9	24 00 25	14.55	5	1.37	K7	10	...		0.97	
1284[d]	3 44 05.7	23 50 32	8.37	1	0.30	A9	2	100	3	...	
1298	3 44 08.6	23 33 44	12.18	1	1.02	K2		10		0.98	

TABLE 2—*Continued*

Hz II	R.A. (1950)	Decl. (1950)	m_v	Ref.	$B-V$	Sp[a]	Ref.	V_r[b]	Ref.	P[c]	Notes
1355	$3^h44^m19^s.6$	23°53′03″	14.07	7	1.40	K5	6	<10		0.77	
1380	3 44 22.6	23 39 02	6.99	1	0.03	A1	2	235	3	...	e
1384	3 44 24.8	24 26 09	7.66	1	0.21	A4	2	215	3	...	
1431	3 44 30.6	24 08 09	6.81	1	0.06	A0	2	40	3	...	
1454	3 44 34.3	24 31 54	12.82	9	1.14	K5	10	<10		0.97	
1514	3 44 34.4	24 12 44	10.48	1	0.64	G1		...		...	
1516	3 44 41.4	24 08 58	13.87	5	1.27	K6		...		0.99	f
1531	3 44 42.9	23 49 11	13.41	9	1.22	K5		50		0.94	g

[a] Spectral type computed according to Allen 1976 from the quoted $B-V$ values, unless otherwise noted.
[b] Equatorial velocity projected along the line of sight (km s^{-1}), from Stauffer *et al.* 1984, except when otherwise noted.
[c] Probability of cluster's membership according to Jones 1973.
[d] Star present in the overlap region of the two exposures.
[e] Double system; data from Binnendijk 1946, except when otherwise noted.
[f] Flare star; data from Binnendijk 1946, except when otherwise noted.
[g] Photometric periodic variable (Van Leewen and Alphenaar 1982, Alphenaar and Van Leewen 1981).

REFERENCES.—(1) Johnson and Mitchell 1958. (2) Mendoza 1956. (3) Anderson, Stoeckly, and Kraft 1966. (4) Wilson 1963. (5) Landolt 1979. (6) Kraft and Greenstein 1969. (7) Stauffer 1980, Stauffer *et al.* 1984. (8) Kraft 1967. (9) Jones 1973. (10) Herbig 1962.

1981). Only six stars (~7% of the stars from A to K) in the Hyades survey have been detected as X-ray sources with luminosities above the threshold for our Pleiades survey. Since the primary difference between these two open clusters is their age (the Pleiades being ~1/10 the age of the Hyades), it is natural to attribute this difference in X-ray luminosity to this age difference (or to stellar attributes which vary with stellar age); this point of view is also consistent with the expected decline of stellar activity with time for any given star.

More specifically, Stern *et al.* (1981) detected ~80% of the Hyades G dwarf stars, finding that the median X-ray luminosity for these stars (~$10^{29.1}$ ergs s^{-1}) is approximately 30 times the X-ray luminosity of the Sun (which is ~10 times older than the Hyades stars). Among the Hyades stars, three out of 13 G dwarfs have X-ray luminosity above 2.5×10^{29} ergs s^{-1}; in comparison, we find that more than half of the Pleiades G dwarfs emit above this threshold. Since the Hz catagog is not complete for K stars, the comparison of detection statistics for K stars is not as meaningful as for the G stars. However, while Stern *et al.* did detect in X-rays only one out of the 18 K stars in their combined field of view at a level above 3×10^{29} ergs s^{-1}, we have detected six (or seven, if one assumes the source which has not been identified to be a K star) out of more than 26 K stars. Thus a clear decline in activity level (as measured by the stellar X-ray luminosity) with age is evident. This decline is illustrated in Figure 5, in which

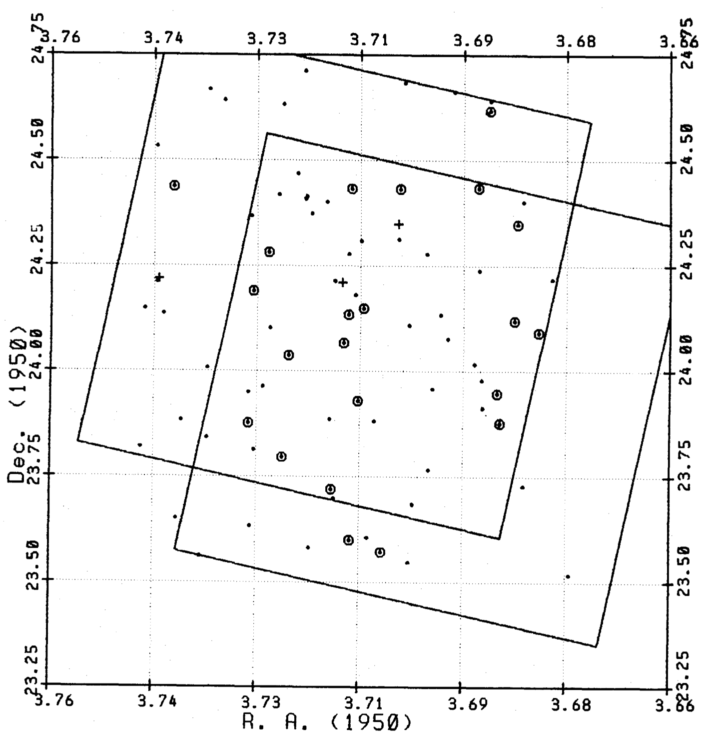

FIG. 1.—Schematic map of the two IPC fields, showing the location of the surveyed Pleiades stars (*points*) and the X-ray sources detected (*circles*). The crosses indicate three X-ray sources not identified with cluster members. Noncluster stars are not shown.

TABLE 3

X-Ray Luminosities of Stars in the Survey
(10^{29} ergs s^{-1})

Hz II	Spectral type	I 5458	I 5457	Hz II	Spectral type	I 5458	I 5457
120	F6	...	<7.8	785	B7 III	<1.6	<2.4
158	A7	<2.7	<4.6	793	K8	<3.8	<6.2
193	G7	6.3 ± 1.6	3.5 ± 1.2	799	K3	2.9 ± 1.5[a]	<3.7
232	A5	...	<3.2	804	A2	...	<1.9
233	F7	...	<2.0	817	B8	<1.8	...
253	G1	...	22.4 ± 3.2	859	B9	<1.6	...
263	G8	4.6 ± 1.7[a]	5.4 ± 1.6	870	K5	...	<2.5
298	G + K }	2.9 ± 1.4[a]	4.8 ± 1.4	879	K2	<1.8	<6.0
299	G + K }			883	K4	<1.8	<6.4
303	G9	14.4 ± 2.3	5.2 ± 1.6	885	K3	<2.4	...
314	G1	<8.7	...	916	G8	<1.5	<3.9
320	G5	8.8 ± 2.6	...	956	F0	<4.1	<8.3
324	K2	<8.7	...	974	K7	<2.2	...
335	K5	<6.5	<2.6	980	B6 IV	4.2 ± 1.6[a]	...
338	F2	...	<2.9	996	G1	<2.1	<4.8
344	A8	<1.7	<2.8	1028	A2	<1.4	<2.4
345	G8	12.7 ± 1.9	10.9 ± 2.7	1032	G8	8.2 ± 1.4	6.9 ± 2.4[a]
357	K6	...	<3.0	1061	K5	<2.2	<3.0
405	F9	<4.4	...	1094	K8	<2.8	<3.5
430	G8	<1.6	<2.1	1100	K3	2.8 ± 1.0[a]	3.7 ± 1.7[a]
447	B7 IV	<1.4	<1.9	1110	K6.5	<1.6	<5.4
468	B6 III	<1.7	<1.5	1117	G6	...	<12.8
476	G1	<2.7	<2.1	1122	F4	...	<3.5
489	G0	<1.8	<5.2	1124	K0	<3.2	4.3 ± 1.8[a]
522	K2	<2.2	<2.5	1207	G1	<8.4	...
530	F3	...	<2.6	1266	F2	<4.1	...
531	Am?	<1.4	<1.9	1280	K7	<2.1	<4.3
541	B8	<2.9	...	1284	A9	<1.8	<3.4
554	K5	2.0 ± 0.9[a]	<3.1	1298	K2	...	<8.0
563	B6	<2.1	...	1355	K5	<3.1	...
625	K3	...	5.9 ± 1.7	1380	A1	...	<6.8
652	A3	...	<1.9	1384	A4	13.1 ± 2.1	...
676	K3.5	...	<3.6	1431	A0	<2.0	...
686	K2	<2.0	3.1 ± 1.5[a]	1454	K5	<2.2	...
697	A9	<1.6	<3.1	1514	G1	<5.0	...
708	G0	4.7 ± 1.2	2.9 ± 1.2[a]	1516	K6	<2.6	...
717	A1	<1.6	<2.0	1531	K5	<5.8	...
727	F9	9.1 ± 1.5	...	X-1[b]	...	4.1 ± 1.0	...
738	G5	...	6.5 ± 2.0	(938/939)	K		
745	F5	<1.9	3.4 ± 1.5[a]	X-2[b]	...	2.8 ± 0.98	...
746	G5	<1.4	<3.1	(1053)			
761	G1	3.3 ± 1.0	<2.7	X-3[b]	...	5.0 ± 1.5	...

[a] Count rate determined at the star location, 2 σ above local background (see text).

[b] The X-ray sources not associated with cluster members are at:

$$\alpha_1 = 3^h43^m15^s \quad \delta_1 = 24°01'49''$$
$$\alpha_2 = 3\ 43\ 33 \quad \delta_2 = 24\ 04\ 08$$
$$\alpha_3 = 3\ 44\ 34 \quad \delta_3 = 24\ 13\ 08$$

X-1 is within 1′ of the FO cluster member Hz II 956, but the source centroid is also near the field binary system. Hz II 938-939. This system is nearer than the Pleiades and contains a K star, so we tentatively identify X-1 with Hz II 938-939. Hz II 1053 is not a cluster member.

we plot the average detection threshold, the median, and the highest detection for X-ray observations of G spectral type T Tauri stars (Ku and Chanan 1979), Pleiades stars (this paper), Hyades stars (Stern *et al.* 1981), and local disk population members (Vaiana *et al.* 1981).

In order to quantify this behavior we have constructed maximum-likelihood luminosity functions (Avni *et al.* 1980; Schmitt 1984) for both the Pleiades and Hyades G dwarf stars. The Pleiades data used for these calculations are given in Table 3; the results of our computation for the Pleiades and Hyades are shown in Figure 6. We have applied a "bootstrap" calculation in order to compute the mean luminosities for the two clusters, including errors (Efron 1982; Schmitt 1984); we find that

$$\langle L_x \rangle_{\rm Pleiades} = 10^{29.6 \pm 0.1}\ {\rm ergs\ s^{-1}}\ ;$$
$$\langle L_x \rangle_{\rm Hyades} = 10^{29.1 \pm 0.1}\ {\rm ergs\ s^{-1}}\ .^4$$

We can therefore conclude that the Pleiades G stars have a

[4] We note, however, that the results reported by Stern *et al.* (1981) were obtained with the "Rev O" version of the *Einstein* data-analysis software, while our results for the Pleiades stellar cluster we obtained using the updated "Rev 1" software; for this reason, there might be small (~10%) discrepancies between our paper and theirs in the luminosity levels of stars.

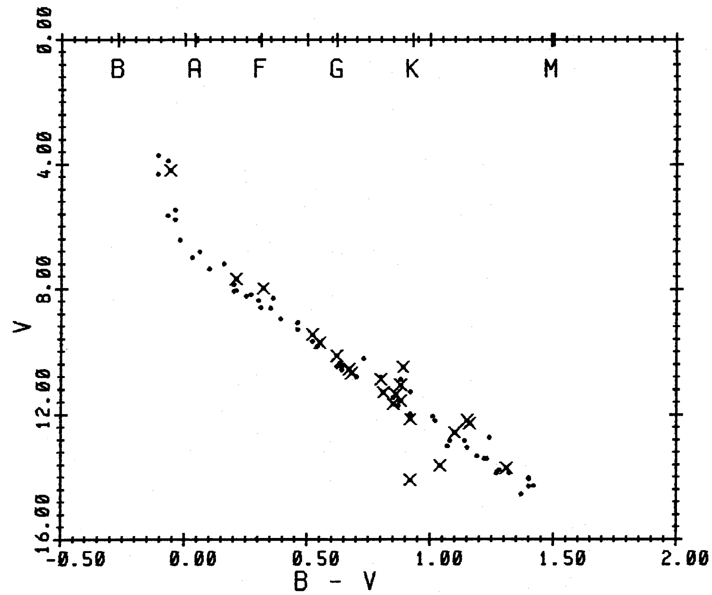

FIG. 2.—H-R diagram for the Pleiades stars in the two IPC fields. X's represent X-ray detections at a level of significance above 2 σ.

significantly (>3 σ) higher level of X-ray emission than the Hyades G stars.

We have also compared the range of the X-ray luminosity for Pleiades stars in our survey that have $0.4 < B-V < 1.0$ with a similar sample of stars belonging to the Ursa Major cluster (Walter *et al.* 1984); specifically, the value of L_x for UMa members ranges between $10^{28.9}$ and $10^{29.6}$ ergs s^{-1}, while for Pleiades stars in our survey L_x ranges between $10^{29.3}$ and $10^{30.3}$ ergs s^{-1}. Because the UMa cluster is older than the Pleiades cluster, this result is consistent with a trend of decreasing level of X-ray emission with stellar age. A more detailed comparison is not possible at this time because of the lack of upper bounds information for the UMa cluster.

In spite of the above reassuring evidence that stellar activity indeed declines as the stellar population ages, the Pleiades data also suggest that the sample picture in which the stellar-activity level of late-type stars is dominantly determined by the stellar-rotation rate, so that the age dependence is introduced by, for example, slow-down in the stellar spin rate, is not the entire story. In particular the absence of sources definitively

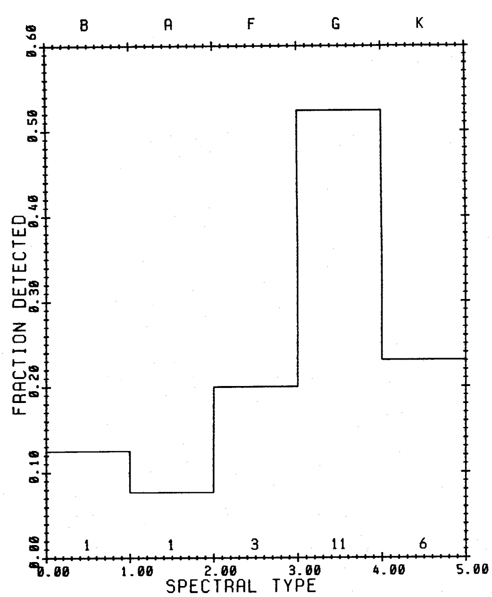

FIG. 3

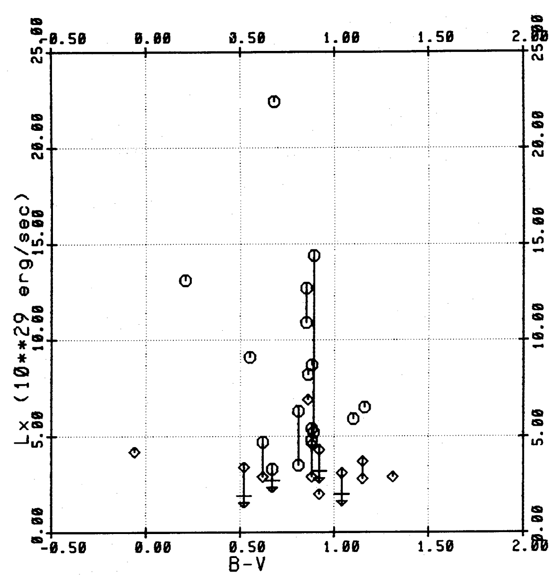

FIG. 4

FIG. 3.—X-ray detection statistics for the Pleiades stars; we show both the fraction of the total number of stars in each spectral-type range which were detected and the number of individual sources observed in each spectral type (given as numbers at the bottom of each bin). Note that the detection fraction shown for the K stars is an upper limit because the Hz II optical catalogue is complete only to $m_V = 14$.

FIG. 4.—Summary of X-ray detections, represented by diamonds (2 σ level) and octagons (3 σ level). For stars observed in both IPC fields, the detections (or detection and constraining upper limit) are joined by a solid line.

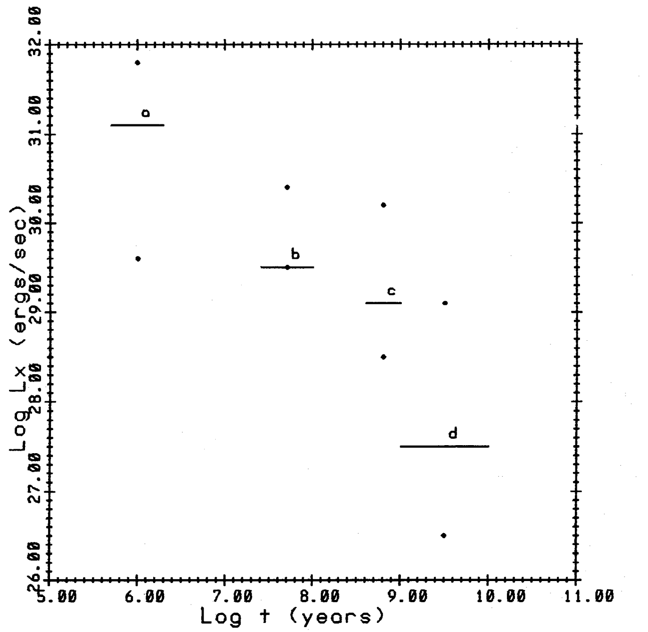

FIG. 5.—Dependence of the median X-ray luminosity on age for different samples of G stars. Bars are located at the values of the median X-ray luminosity; their length represents the uncertainty in age determination in each group. The range of observed luminosities is indicated by ● (the lower ● is always fixed by the detection threshold in each group). (*a*) Pre–main-sequence G stars (Ku and Chanan 1979; Feigelson and De Campli, 1981); (*b*) Main-sequence G stars in the Pleiades (present survey); (*c*) Main-sequence G stars in the Hyades (Stern *et al.* 1981); (*d*) Local disk population dwarf G stars (Vaiana *et al.* 1981; Topka *et al.* 1982; Rosner *et al.* 1981).

identified with M dwarf stars is very puzzling. To see this, note that the median X-ray luminosity of Pleiades dG stars is ~ 50 times as large as the value found by Vaiana *et al.* (1981) for field dG stars. Then, if we assume that the X-ray luminosity function for the Pleiades dM stars is shifted by the same amount from that of the field stars, assume that the number of Pleiades M stars is ~ 10 times larger than that of G stars, (as is roughly the case for galactic-disc stellar-space densities; Allen 1976), and use the X-ray luminosity function of field dM stars derived by Rosner *et al.* (1981), we find that ~ 10 dM stars should have been seen above the threshold of our survey. Instead, we have observed only one source (X-3 in Table 3) which could possibly correspond to an uncatalogued M star; there are no other unidentified sources. We therefore conclude that the luminosity scaling with age must be spectral-type–dependent, as would occur if there were another stellar parameter (dependent upon spectral type) which figures in determining stellar activity level. The most plausible such parameter is the outer stellar convection depth; for example, Schmitt *et al.* (1985) have suggested that the activity level of dF stars is correlated with the Rossby number at the basis of the convection zone, and is thus related to a particular combination of rotation rate and convection zone depth (see also Noyes *et al.* 1984 for such evidence derived from Ca II data). We further note that the above argument derived from the (non)observation of dM stars is reenforced by a comparison of the X-ray luminosity functions of Pleiades dG and dK stars; using the nonparametric tests described by Schmitt (1984), we find that they are different at a significance level higher than 98%, with the dG star X-ray–luminosity function extending to higher values of L_x than that of the dK stars. This difference is quite remarkable in its own right and will be discussed further below.

b) X-Ray Luminosity and Rotation

Only eight of the stars later than F7 (specifically: four K, one G, three F) in our sample have known values of projected equatorial velocities $v \sin i$; for 11 K stars, we have upper limits to $v \sin i$ and for two stars (one K, one G) we have lower limits to $v \sin i$. In particular, two K, two G, and one F stars detected as X-ray sources have projected equatorial velocity $v \sin i$ in excess of 45 km s^{-1}, while two K stars with $v \sin i > 50$ km s^{-1} were not detected (although their X-ray luminosity upper limits are quite high and hence not very constraining).

Figure 7 shows a log-log plot of X-ray luminosity and $v \sin i$ for stars of types F7 to K in our sample for which velocity measurements or upper/lower limits are available. As a comparison we have plotted the best fit for field stars obtained by Pallavicini *et al.* (1982); we note that the stars in the Pleiades have X-ray luminosities up to 2 orders of magnitude *lower* than RS CVn-type stars with comparable rotational velocity, or than the prediction of the Pallavicini *et al.* (1982) best fit. The RS CVn's are likely to have substantially different behavior in activity-rotation correlations from that of the present sample of stars because the former are close binaries; therefore we have applied nonparametric maximum-likelihood linear regression analysis (including the upper bounds; Schmitt 1984) to our data shown in Figure 7 and to the data of Pallavicini *et al.* (1982), but excluding the RS CVn stars. We obtain $\log L_x \approx 27.5 + 1.5 \log v \sin i$ (solid line in Fig. 7), instead of the quadratic relationship between X-ray luminosity and projected equatorial velocity obtained by Pallavicini *et al.* (1982). Our regression function is, however, a poor fit to these data, suggesting that a single power law of the type applied here is not an adequate description of the data even in the RS CVn–excluded combined sample.

c) The Rapidly Rotating but Relatively Inactive K Dwarfs

Given the currently popular notion that stellar activity levels ought to correlate well with stellar rotation rates, it seems surprising that the Pleiades K dwarfs have systematically lower activity levels than the corresponding G dwarfs (shown most succinctly by the detection histogram in Fig. 3), because the dK

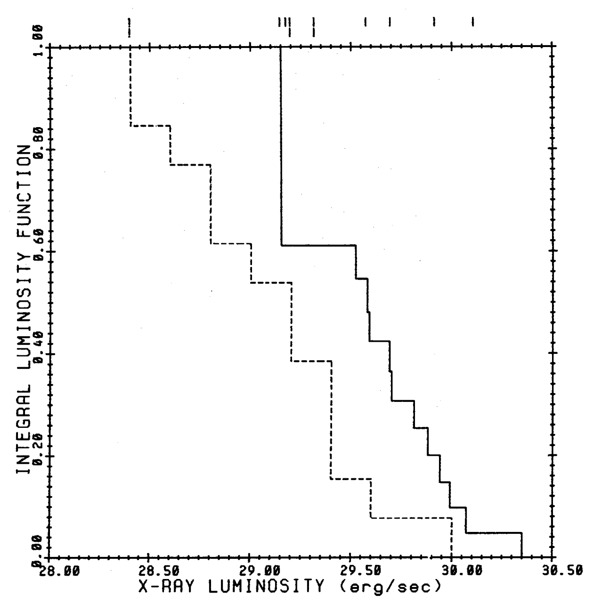

FIG. 6.—Maximum-likelihood integral X-ray luminosity functions of Pleiades (*solid line*) and Hyades (*dashed line*) G dwarfs.

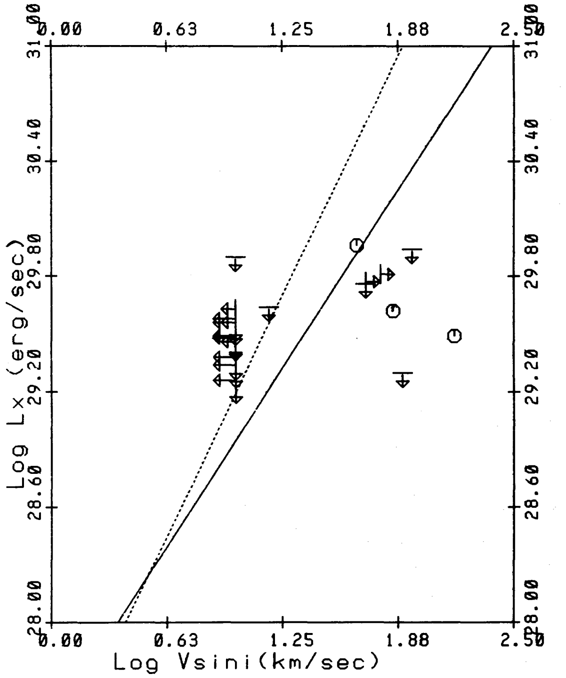

FIG. 7.—Log of the X-ray luminosity vs. the log of the projected equatorial rotational velocity for the Pleiades stars later than F7 for which values of, or bounds on, these velocity are known. Our data are shown as octagons when we have measurements for both the values of L_x and $v \sin i$. When only one of the two quantities has been measured (so that we know an upper or lower limit for the other quantity), the corresponding limit is indicated by an arrow pointing in the appropriate direction; when we have only upper/lower limit information on both variables, this is indicated by double arrows. For comparison, we also plot (*dashed line*) the best fit of Pallavicini *et al.* (1981) including normal dwarf stars, RS CVn's, T Tauri stars, and Hyades stars. The solid line represents the linear regression (including upper limits, Schmitt 1984) to all data without including the RS CVn's: $\log L_x \approx 27.47 + 1.48 \log v \sin i$.

stars in this cluster include a number of rapid rotators (cf. Stauffer *et al.* 1984). We believe that one can, however, account for this behavior. As suggested by the solar rotation evolution models of Endal and Sofia (1981), rapid evolution on the radiative track leads to spin-up of the entire star, which is followed by rapid spin-down (by magnetic braking) of the outer convective envelope. If, on average, the K stars in our sample correspond to the former evolutionary stage, while the G stars (again on average) correspond to the latter stage, then one would expect the rapidly rotating K dwarfs to have relatively modest rates of internal differential rotation at the convection zone–radiative core interface, whereas more slowly rotating G dwarfs would still have (at least just after the rapid envelope spin-down period) a rapidly spinning core and hence substantial differential rotation at this interface.

This scenario is supported by the fact that, at the nominal Pleiades age of $\sim 10^{7.7}$ yr, a solar-like star would have just reached the zero-age main sequence, as shown by Figure 5 of Endal and Sofia (1981). Such a star would already show a greater than threefold difference between its surface rotation rate and the (larger) radiative core rotation rate. In contrast, a lower mass K dwarf at the Pleiades age would not have reached this stage as yet, and the consequent maximum difference in rotation rate between the core and the surface would be less than twofold.

As has been recently suggested by Rosner (1980), Spiegel and Weiss (1980), and Golub *et al.* (1981), the presence of a shear near the base of an outer convective zone is highly favorable to a "shell dynamo" driven by a gradient in Ω at the convective envelope–radiative core boundary. Hence, one would expect on this model, at least qualitatively, that magnetic activity is most vigorous just at the point at which this differential rotation is maximized, thereby accounting for the observed difference in activity levels in the Pleiades G and K dwarfs. This scenario would also account for the paucity of X-ray sources associated with the dM stars in our Pleiades fields. This interpretation is not in contradiction with the observed high level of X-ray emission in T Tauri stars (e.g., Ku and Chanan 1979) both because the interior state of these stars is highly uncertain and because of the possible influence of primordial magnetic fields.

d) A Stars

The only A star which has been detected in X-rays in this survey (Hz II 1384) has an extremely high X-ray luminosity: $L_x \approx 1.3 \times 10^{30}$ ergs s^{-1}, i.e., three orders of magnitude higher than the value indicated as typical by Golub *et al.* (1983) in their survey of A stars detected by *Einstein.* As shown by Schmitt *et al.* (1984), A stars detected at peculiarly high values of X-ray luminosity are very likely in multiple systems in which the X-rays are dominantly emitted from an unseen late-type companion; however, Abt *et al.* (1965) have not found Hz II 1384 to be a spectroscopic binary. Furthermore, if we are to take the argument presented above seriously (and consider the relative dearth of detections of such stars), then any dK or later spectral-type companion ought not to be a vigorous X-ray source; instead, the X-ray luminosity of Hz II 1384 places it at the very upper end of the dG star luminosity function, and hence well above the emission levels observed and expected for later spectral type stars. Thus, although there is substantial observational motivation based on surveys of field dwarf A stars to place a strong upper bound on the possible contribution of the A star (in the hypothesized binary system) to the observed X-ray luminosity, the alternative (namely the presence of any lower-mass companion to this A dwarf which is responsible for the observed emission) appears to be problematic (as it would require a dG companion which is exceptionally bright in X-ray and which has escaped optical detection).

Given this difficulty, we would like to consider one remaining alternative explanation, which is even more speculative. A stars also go through a fully convective (well-mixed) stage during the descent to the main sequence; in this well-mixed regime, *large* radial gradients in rotation rate are unlikely. However, since the radial contraction which occurs during descent to the main sequence is nonhomologous, there must be a regime during which the star is (at least partially) convective and strongly differentially rotating. These circumstances are suitable for magnetic dynamo action, but continued dynamo action is not very plausible once the star has reached the main sequence (because convection ought to have ceased). Hence it may be that the observed activity is due to the dissipation of the magnetic fields produced during such an evanescent magnetically-active regime. This speculative suggestion seems to be consistent with the fact that the normal-field dA stars show no evidence for "activity" (Schmitt *et al.* 1985), but that dA stars known to be associated with strong surface magnetic fields (i.e., A_p stars such as ω Oph and α CVn) have been detected in X-rays, with $L_x \approx 10^{29}$ ergs s^{-1} (Golub *et al.* 1983).

e) Variability

We have searched for variability between the two IPC observations (i.e., on a time scale of ~1 day) for all the stars in the overlap region which were detected above the 3 σ level in both exposures. Our analysis detected variability (at a level of 3.3 σ) only in the X-ray flux of the star Hz II 303, which varied by a factor of ~3. No significant variability information could be obtained for the remaining stars in the overlap region.

IV. SUMMARY

We have analyzed the data obtained with two pointed observations of 1° × 1° fields of the Pleiades region, have derived the maximum-likelihood X-ray luminosity functions for the Pleiades G and K stars in the cluster, and have shown that for the G stars, the Pleiades X-ray luminosity function is significantly brighter than the corresponding function for Hyades G dwarf stars. This finding indicates a dependence of X-ray luminosity on stellar age, which is confirmed by comparison of the same data with median X-ray luminosities of pre–main-sequence and local-disc-population dwarf G stars. Furthermore, although they are bright in X-rays, the X-ray luminosity of late-type Pleiades stars falls generally below the predictions of the $L_x \approx (v \sin i)^2$ relation of Pallavicini *et al.* (1981), for late-type main-sequence stars, indicating that such a simple relation between X-ray luminosity and rotational velocity for late-type stars is not an adequate description of the full data.

We have suggested that the significantly larger number of bright X-ray sources associated with G stars than with K stars, the lack of detections of M stars, and the relatively rapid rotation of the Pleiades K stars (Stauffer *et al.* 1984), can be explained in terms of the onset of internal differential rotation near the convective envelope–radiative core interface after the spin-up phase during evolution to the main sequence. In this picture, the K stars are still spin-up, and have relatively little differential rotation, while the G stars have already started the spin-down by magnetic braking, thereby developing a gradient in angular velocity at the boundary between a fast rotating core and a slower convective envelope. Finally the detection of an A star in the cluster as a vigorous X-ray source cannot be readily accounted for by invoking either intrinsic emission along the lines of the "solar analogy," or an unresolved low-mass, active companion, raising the question whether the observed emission is the "aftermath" of an earlier epoch of magnetic dynamo activity during the descent of the (convecting) progenitor star to the main sequence.

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