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STELLAR CORONAE IN THE HYADES: A SOFT X-RAY SURVEY WITH THE *EINSTEIN* OBSERVATORY

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ABSTRACT

An X-ray survey of the central region of the Hyades cluster with the *Einstein* Observatory has demonstrated that soft X-ray emission is a common property of the stars in the cluster. Of the 85 stars surveyed, about half are detected above a sensitivity threshold of $\sim 10^{28.5}$ ergs s^{-1} (0.2–4.0 keV) at the Hyades distance ($\sim$45 pc). More than 80% of the F and G dwarfs are X-ray sources, as well as three Hyades giants (θ^1 Tau, γ Tau, and δ Tau). The brightest X-ray source is 71 Tau ($L_x \gtrsim 10^{30}$ ergs s^{-1}), a rapid rotator ($v \sin i \sim 200$ km s^{-1}) of spectral type F0 V. The high incidence of X-ray emission and range of observed X-ray luminosities provide convincing evidence that stellar coronae produce the observed X-ray emission. These coronae, however, are significantly brighter than that of the Sun: the typical X-ray luminosity for solar-type Hyades is $\sim 10^{29}$ ergs s^{-1}, or $\sim$30 times that of the Sun in an active phase; one G1 dwarf, HD 27836, has an X-ray luminosity of $\sim 10^{30}$ ergs s^{-1}, or $\sim$300 times that of the Sun. Our data cannot be explained by simple acoustic heating models. It is likely that the relatively rapid rotational velocity of the Hyades solar type dwarfs compared to the Sun is an important factor in producing enhanced X-ray activity: if L_x depends upon rotation in a simple way for solar type dwarfs, i.e., $L_x \propto v_e^\alpha$ or Ω^α, our data suggest $\alpha \approx 2$. The use of coronal scaling laws yields reasonable values of maximum coronal temperature and fraction of stellar surface area covered for the Hyades coronae. Follow-up studies with *Einstein* and *IUE* are currently under way to better restrict these and other coronal model parameters.

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

I. INTRODUCTION

Stellar X-ray astronomy has recently achieved a new prominence as a direct result of observations from the *HEAO 1* and *HEAO 2* (*Einstein* Observatory) satellites. Except for the low energy components of classical X-ray binaries having high X-ray luminosities in the 2–10 keV band ($L_x \sim 10^{36}$–10^{38} ergs s^{-1}), soft X-ray ($E \lesssim 2$ keV) stellar sources were at first restricted to fairly unusual objects, such as RS CVn systems (Walter, Charles, and Bowyer 1978), hot white dwarfs (Lampton *et al.* 1976; Margon *et al.* 1976), dwarf novae (e.g., Mason *et al.* 1978), or binaries with magnetic white dwarfs such as AM Her (e.g., Szkody *et al.* 1980). Only a few "normal" systems such as α Cen (Nugent and Garmire 1978), Sirius (Mewe *et al.* 1975; Lampton *et al.* 1979), and Vega (Topka *et al.* 1979) were detected with rocket experiments or *HEAO 1*. Observations from *Einstein* have changed this picture dramatically, demonstrating that soft X-ray emission is a common phenomenon in stars (Vaiana *et al.* 1981; Walter and Bowyer 1981; Ku and Chanan 1979; Long and White 1980). The observed X-ray luminosities (10^{27}–10^{32} ergs s^{-1}) and soft spectra ($kT \lesssim$ several keV) strongly suggest that coronae, or in some cases winds, are responsible for such stellar X-ray emission.

Because theories of the formation and heating of stellar coronae are at present in a primitive state (Vaiana and Rosner 1978; Linsky 1980*a*, *b*), it is important to accurately determine the functional dependence of stellar X-ray luminosity on such parameters as spectral type, luminosity class, rotation, and elemental abundances. Earlier models of acoustic wave heating (e.g., Mewe 1979) based upon homogenous plane-parallel

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atmospheres, and neglecting the effect of plasma confinement by magnetic fields, fail to explain even solar observations (Bruner 1979; Athay and White 1978). The order-of-magnitude or more variation of X-ray luminosity among stars of the same spectral and luminosity class is also not accounted for by simple acoustic heating models (Vaiana *et al.* 1981).

Much as the study of stellar clusters has proven a key step in understanding stellar evolution and the evolutionary state of the Sun, similar studies in soft X-rays promise to be highly fruitful in understanding stellar coronae. Known distance, homogeneous composition, and equality of age are among the advantages of cluster surveys which will help decouple the influence of individual stellar parameters on X-ray emission.

The Hyades cluster has been thoroughly observed optically because of its importance as a distance standard and calibration point for stellar evolution (van Bueren 1952; van Altena 1966, 1969; Pels, Oort, and Pels-Kluyver 1975; Hanson 1975; Oort 1979). It is also an excellent choice for an X-ray survey, because of its proximity ($d \sim 45$ pc: Hanson 1980), and an indicated low X-ray absorption from ultraviolet and visible measurements (Bohlin, Savage, and Drake 1978; Taylor 1980). In this paper we report the results of an extensive survey of the cluster center ($\sim 5°$ diameter) for soft X-ray sources with the *Einstein* Observatory (*HEAO 2*). In § II we discuss the observations, in § III we provide a catalog of the soft X-ray sources detected, in § IV we give an analysis of the survey data, and compare our observations with those from other surveys of stellar soft X-ray sources, in § V we derive constraints on coronal parameters using coronal loop scaling laws, in § VI we discuss our results in the context of coronal heating theories, and in § VII we summarize our results.

II. OBSERVATIONS

The large ($\gtrsim 20°$, Oort 1979) angular extent of the Hyades cluster effectively prohibits a complete survey with the limited observing time available on *Einstein*. However, the central region of the cluster, about 5° or 2 pc diameter at the Hyades distance of 45 pc (Hanson 1980), contains $\sim 50\%$ of the brightest ($V \lesssim 10$) Hyades.

During the period 1979 June to 1980 March, we observed 27 Hyades fields of $\sim 1° \times 1°$ extent with the *Einstein* Imaging Proportional Counter (IPC). The IPC is sensitive to soft X-rays from ~ 0.2 to 4.0 keV (at the nominal gain setting), and yields images with $\sim 1'$–$2'$ resolution, as well as timing and some spectral information (see § III, Giacconi *et al.* 1979; Gorenstein, Harnden, and Fabricant 1981 for more detailed discussions of the *Einstein* Observatory and IPC performance). The effective exposure for each IPC image ranged from ~ 1000 to 4000 seconds; the minimum detectable soft X-ray flux for these exposures was $\sim 1.5 \times 10^{-13}$ ergs cm^{-2} s^{-1}, which corresponds to a limiting X-ray luminosity (L_x) of 3.6×10^{28} ergs s^{-1} at 45 pc.

In Table 1 we list the center coordinates and observing times for each IPC field, and in Figure 1 we show the extent of the survey fields superimposed on a reproduction of Becvar's (1974) stellar atlas, which displays stars brighter than 10th visual magnitude.

Data from the observations were analyzed using the standard *Einstein* production processing routines (*Einstein* Handbook 1979): each field was aspect corrected, and data taken during Earth occultation, South Atlantic anomaly passes, etc., were removed to produce a final X-ray image. These routines also searched each field for evidence of X-ray sources (see § III). A composite image of all 27 fields was then made; this is shown in Figure 2 (Plate 8). Most of the individual X-ray sources are visible in this figure as bright patches (although their apparent visual intensities may be misleading in some cases due to overlapping fields). The variation in background level is largely due to the differing exposure times for each field.

III. A CATALOG OF SOFT X-RAY SOURCES IN THE HYADES

The *Einstein* production processing routines indicated the presence of $\gtrsim 100$ discrete sources in our observing fields. However, from a number of discussions with Observatory scientists (F. Seward, R. Harnden, private communication) and the explanation of source detection routines outlined in the Observatory documentation, we estimate that only about half of these are valid detections. This is because the detection routines indicate the presence of a source using a background level calculated within an annulus of inner and outer radii 8′ and 15′.3 from field center. Since the level of diffuse soft X-ray background observed decreases from field center to edge as a result of telescope vignetting, the production routines will sometimes "detect" spurious sources located near field center and occasionally miss real sources near field edge. We undertook a source-by-source analysis of the IPC images using programs available at the Center for Astrophysics (CFA), the results of which suggest a good correlation with the visual presence of a given source in the IPC image and source strength at a level $\gtrsim 5\ \sigma$ above the actual adjacent background. (In the case of the weakest sources, the maximum likelihood estimator used in the production routines yields a confidence level which is not immediately convertible into a number of "σ" above background; we estimate that such weak sources are at the equivalent of the 3–4 σ level, and such sources are classified as "marginal" in the figures and tables which follow.)

In Table 2 we give the locations, optical identifications, X-ray fluxes, and luminosities (see below) of the sources identified with Hyades cluster members (Pels, Oort, and Pels-Kluyver 1975; Hanson 1975). Approximately 10 sources not associated with known cluster members will be discussed in later publications.

TABLE 1

CENTER COORDINATES AND OBSERVING DATES

IPC Field No.	Center Coordinates (1950)		Observing Date(S)	Total Time in Processed Image (s)
3510	$4^h20^m00\overset{s}{.}0$	15°30′00″	9/10/79	2432
3511	4 28 43.2	15 54 00	9/10/79	1632
3512	4 25 48.0	16 18 36	9/11/79	2964
3513	4 25 48.0	15 30 29	9/09/79	2041
3514	4 31 36.0	16 18 36	9/11/79	1514
3515	4 31 36.0	15 30 00	9/09/79	1902
3516	4 22 55.2	16 42 36	2/20/80	1742
3517	4 20 31.2	15 54 00	9/11/79 2/20/80	2654
3518	4 22 55.2	15 06 00	9/09/79	1981
3519	4 20 00.0	17 06 36	3/07/79	2291
3520	4 20 00.0	16 18 36	3/07/79	1159
3521	4 20 00.0	14 41 24	9/09/79 2/19/80	3449
3522	4 20 00.0	13 53 24	9/09/79 2/10/80	2956
3523	4 22 55.2	14 17 24	9/09/79 2/19/80	3336
3524	4 25 48.0	14 41 24	9/09/79 2/20/80	3316
3525	4 28 43.2	15 06 00	9/09/79 2/20/80	2544
3526	4 28 43.2	16 42 36	9/11/79 3/03/80	2013
3527	4 25 48.0	17 06 36	3/02/80	2044
3528	4 22 55.2	17 31 12	3/02/80	4245
3662	4 31 36.0	14 41 24	2/20/80	3159
3663	4 17 4.8	15 06 00	2/10/80	2653
3664	4 17 4.8	15 54 00	2/10/80	1951
3665	4 17 4.8	14 17 24	2/10/80	2576
3666	4 17 4.8	16 42 36	2/10/80	3211
3667	4 17 4.8	17 31 12	2/20/80	1852
3668	4 20 00.0	17 55 12	9/09/79 2/20/80	3433
4476	4 22 55.2	15 54 00	9/10/79	1624

Optical identifications of the X-ray sources were determined by noting the centroid of position given by the IPC production routines and searching for a Hyades optical counterpart within a circle of $\sim 2'$ radius. In $\sim 80\%$ of the sources which met our detection criteria, a Hyades optical counterpart was found; most of these were within $\sim 1'$ of the X-ray position (see Table 2). Since there is an average of ~ 2 X-ray sources per IPC field and an average of ~ 3 Hyades stars with $V \lesssim 16$ in each field, and since the effective angular resolution of the IPC is $\lesssim 2'$, the probability that any given optical identification is due to chance alone is $\lesssim 10^{-4}$. Searches of radio source and nonstellar optical source catalogs (Dixon 1970*a*, *b*, 1978, 1979) have produced no alternative identifications for X-ray sources associated with Hyades stars. In Figure 3 we plot an H-R diagram of the Hyades in our observing fields, indicating those that were detected as soft X-ray sources.

Two methods were used to derive X-ray fluxes. For the stronger sources, we used computer programs available at CFA to calculate source counts in a circular area centered at the best source position and an annulus centered at the same location to calculate adjacent background. Pulse-height data from the IPC were fitted to thermal spectra with assumed values of kT from 0.1 to 10 keV, increasing the assumed source temperature until

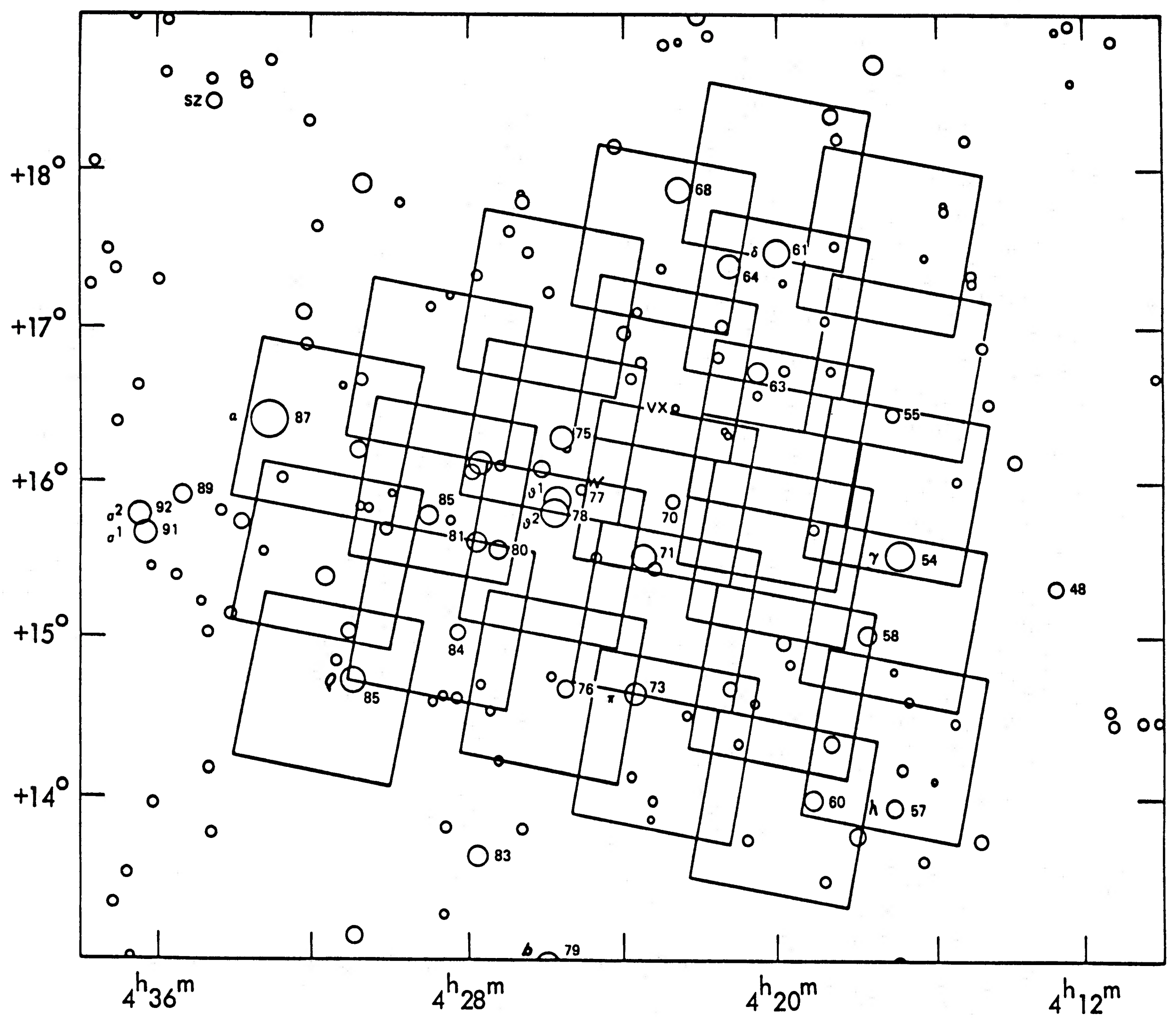

FIG. 1.—Survey fields. Size of circle indicates visual magnitude from Becvar (1974).

further changes in the calculated flux were $\lesssim$20% due to the matching of high energy X-ray cutoff and exponential dropoff of the assumed spectra (the temperature estimated here is not a good indication of true source temperature because of spatial variations in the IPC gain: see below). We found very good agreement between fluxes derived using this method and the direct conversion of IPC counts per second (cts s^{-1}) to X-ray flux used by Vaiana *et al.* (1981) of $\sim 2 \times 10^{-11}$ ergs cm^{-2} s^{-1} per IPC ct s^{-1} for an assumed thermal spectrum at $kT \sim 1$ keV. For weaker X-ray sources, where counting statistics are the largest sources of error, we therefore used the above conversion factor to estimate fluxes. All fluxes are listed in Table 2.

In the analysis that follows, we have not included a discussion of X-ray spectral information from the IPC. Because there are systematic variations of the IPC gain over angular sizes comparable with the spatial resolution of the IPC, derived constraints on temperature for our sources are highly uncertain at present. New spectral fitting procedures currently being developed at CFA may alleviate this problem in the future (R. Harnden, private communication).

The X-ray luminosity (L_x) for each Hyades source was derived using the fluxes in Table 2 and the individual distance of each star calculated using the proper motion and cluster convergent point data of Hanson (1975). Errors in the derived values of L_x, which we estimate as $\sim$35–60%, may come from a number of sources: (1) the statistical counting errors, which range from $\sim$5% for the brightest sources to $\sim$50% for the weakest; (2) systematic errors in converting IPC cts s^{-1}

TABLE 2

Hyades X-Ray Source Catalog

HEX #[a]	HD	Other[b] Desig.	Sp[c]	V	$B-V$[d]	IPC Field(s)	Optical Coordinates (1950)	Difference between X-Ray and Optical and Position (′)	X-Ray[e] Flux (10^{-13} ergs cm^{-2} s^{-1})	Log L_x (ergs s^{-1})	Comments[f]
1	27130	+16°577	G8 V	8.3	0.77	3666	$4^h14^m46^s$, 16°49′36″	0.75	5.0E	29.1	$P_h \lesssim 10\%$, SB,[g] $p=5^d.6$
2	...	+17°704	K	10.0	1.1	3667	4 15 29, 17 18 05	0.5	10.0	29.4	
3	27282	+17°707	G8 V	8.5	0.72	3667	4 16 15, 17 24 19	1.0	6.0	29.3	
(4)	...	VR 1 = vA 162	M1	12.8	1.4	3665	4 16 31, 14 11 48	0.3	~1	28.4	
5	27371	γ Tau	K0 III	3.6	0.99	3663	4 16 57, 15 30 31	0.3	8.5	29.4	
						3664		0.9			
6	27383 AB	55 Tau	F8 V	6.9	0.56	3664	4 17 03, 16 24 14	0.5	4.8	29.0	ADS 3135
						3666		1.25			
(7)	27483	+13°665	F6 V	6.2	0.46	3522	4 18 04, 13 44 47	1.3	1.5	28.5	SB[h]
8	27534	+18°629	F6 V	6.8	0.44	3668	4 18 38, 18 18 02	0.9	2.0	28.7	
9	27561	+14°687	F4 V	6.6	0.41	3665	4 18 45, 14 17 34	0.6	5.5	29.0	
						3522		0.7			
						3521		0.5			
10	27628	60 Tau	F0 m	5.7	0.32	3522	4 19 14, 13 57 39	0.3	3.3	29.2	SB[h]
11	27685	+17°585	G4 V, G5	7.9	0.68	3519	4 19 52, 16 40 32	1.3	4.0	28.8	
						3520		0.2			
12	27691 AB	+14°690	G0 V	7.0	0.56	3521	4 19 54, 14 56 25	0.3	8.0	29.2	SB,[h] $p=4^d$; ADS 3619
									16.0	29.5	
13	27697	δ Tau	K0 III	3.8	0.98	3519	4 20 03, 17 25 37	0.3	2.7R	28.9	
(14)	...	VR 4 = vA 276	K4?	10.5	1.24	3517	4 20 34, 15 38 54	1.3	1.6	28.6	
(15)	27771	+14°691	K1 V	9.1	0.87	3521	4 20 42, 14 33 19	0.5	~1	28.4	
16	...	VR 6 = vA 288	M2–3	13.4	1.55	3521	4 21 00, 14 48 26	0.3	3.7	28.9	Flare star
(17)	27819	64 Tau	A7 V	4.8	0.16	3528	4 21 13, 17 19 47	1.6	~1	28.5	
18	27836	+14°693	G1 V	7.6	0.60	3518	4 21 22, 14 38 38	0.2			
						3521		0.3	40	30.0	
						3523		0.8			
19	27859	+16°592	G1 V	7.8	0.60	3516	4 21 36, 16 46 21	1.2	5.2	29.1	
20	...	vA 334	dM; M0e	11.6	1.4	3517	4 21 56, 15 45 41	0.2	1.5	28.8	
						4476		0.5			
21	...	vA 351 = LP 415–65	M2	13.5	1.54	3516	4 22 20, 17 09 19	0.3	3.3	29.0	Flare star
						3528		0.5			
22	27962	68 Tau	A2 IV, –A3 V	4.3	0.05	3528	4 22 36, 17 48 55	0.7	2.4	28.9	vis. bin.
23	27991	70 Tau	F7 V	6.5	0.49	4476	4 22 46, 15 49 42	0.3	12	29.4	vis. bin.
(24)	...	vA 362 = LP 415–71	K–M	15.3	1.49	3528	4 22 53, 17 25 57	1.0	~1	28.5	
25	27990	+17°718	K0	9.0	0.94	3528	4 22 54, 17 54 18	0.2	3.3R	29.2	
26	28034	+15°624	F8 V	7.5	0.54	3518	4 23 15, 15 24 44	0.7	4.2R	28.9	
27	28052	71 Tau	F0 V	4.5	0.25	3518	4 23 30, 15 30 23	0.7	40	30.1	
						4476		0.2			

TABLE 2—*Continued*

HEX #[a]	HD	Other[b] Desig.	Sp[c]	V	$B-V$[d]	IPC Field(s)	Optical Coordinates (1950)	Difference Between X-Ray and Optical and Position (′)	X-Ray[e] Flux (10^{-13} ergs cm^{-2} s^{-1})	Log L_x (ergs $^{-1}$)	Comments[f]
28	28068	+16°598	G5 V	8.1	0.63	3516	$4^h23^m32^s$, 16°44′29″	0.3	8.2	29.3	
29	28099	+16°601	G6 V	8.1	0.66	3516	4 23 48 , 16 38 07	0.5	13	29.6	
(30)	28205	+15°627	F8 V	7.4	0.54	3513	4 24 45 , 15 28 43	1.2	2.0	28.5	
31	28294	76 Tau	F0 V	5.9	0.32	3524	4 25 33 , 14 37 53	0.5	1.6	28.6	
32	...	vA 486	M1	12.4	1.48	3527	4 25 35 , 17 35 12	0.2	6.7E	29.3	
33	28307	θ^1 Tau	K0 III+ G2 V	3.9	0.96	3512 3513	4 25 43 , 15 51 10	0.7 0.1	30	30.0	wide binary
34	28344	+16°606	G1 V	7.9	0.61	3527	4 25 55 , 17 10 35	0.2	4.0	29.0	
35	...	VR 17= vA 500	K	10.9	1.37	3512	4 25 59 , 16 10 48	0.6	5.0	29.2	
36	28363 AB	+15°633	F8	6.6	0.53	3512	4 26 08 , 16 03 01	0.2	4.0	28.9	ADS 3248
37	...	vA 512	M1−2	14.4	1.55	3512	4 26 08 , 16 14 16	0.3	1.5	28.7	
38	28394	+17°731	F7 V	7.1	0.50	3527	4 26 27 , 17 26 12	0.2	8.5R	29.2	$P_h \lesssim 10\%$
(39)	28485 AB	80 Tau	F0 V	5.6	0.32	3525	4 27 17 , 15 31 49	1.7	2.5	28.5	$P_h \lesssim 10\%$, ADS 3264
40	28568	+15°640	F5 V	6.5	0.42	3511	4 27 55 , 16 02 30	0.9	10	29.2	
41	28677	85 Tau	F2 V	6.0	0.34	3511	4 29 00 , 15 44 45	1.1	2.0	28.5	$P_h \lesssim 10\%$
(42)	28805	+15°647	G8 V	8.7	0.74	3511	4 30 08 , 15 42 52	1.1	2.5	28.8	
43	28878	+16°620	K2 V	9.4	0.88	3526 3514	4 30 45 , 16 39 31	1.6 1.5	2.5	28.8	
44	...	+14°721	K0 IV−V	8.5	0.84	3662 3515	4 31 08 , 15 03 37	0.6 0.6	1.5	28.5	
(45)	28977	+15°650	K0	9.7	0.91	3515	4 31 40 , 15 43 30	1.6	1.5	28.6	
46	28992	+15°651	G1 V	7.9	0.63	3515	4 31 44 , 15 24 07	0.2	2.4	28.6	
47	...	vA 750= OS 918	M0	12.4	1.45	3515 3662	4 31 49 , 15 06 24	0.07 0.25	4.0	28.7	$P_h \lesssim 10\%$
48	...	vA 763= LP 415−382	M	14.6	2.5?	3515	4 32 37 , 15 17 52	0.4	2.0	28.9	

[a] Hyades *Einstein* X-ray number; parentheses indicates marginal (3–4 σ) detection.

[b] Star name or BD number.

[c] Spectral type from Morgan and Hiltner 1965 or U.S. Naval Observatory Catalog (Blanco *et al.* 1970) if available: otherwise, for fainter stars ($V \gtrsim 10$) from Pesch 1968, 1972, or Luyten 1970.

[d] $B-V$ from above sources or Upgren and Weis 1977 for fainter stars; vA 512 data from J. Stauffer, private communication.

[e] See text for conversion of counts s^{-1} to X-ray flux; *R* indicates flux may be suspect-source location very near IPC rib; *E*, same comment, but source near edge of field.

[f] $P_h \lesssim 10\%$ indicates probability that star is Hyades member (from Hanson 1975; proper motions) is small; note, however, that earlier work (Pels, Oort, and Pels-Kluyver 1975; Van Bueren 1952; van Altena 1966, 1969) indicated these stars as cluster members.

[g] McClure 1980.

[h] Spectroscopic binary.

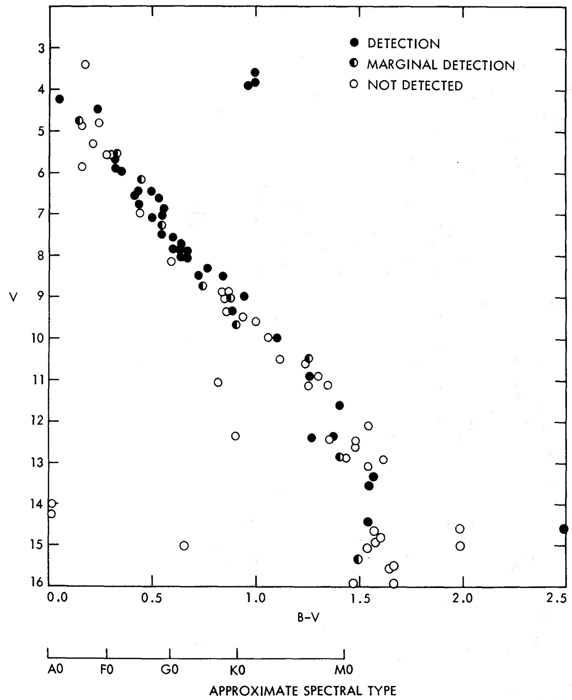

FIG. 3.—H-R diagram of Hyades in survey fields, indicating those detected in soft X-rays (0.2–4.0 keV).

to flux, which are probably $\lesssim$20% (Vaiana *et al.* 1981); (3) errors in the individual stellar distances ($\lesssim$10%), which contribute $\lesssim$20% errors in luminosity; (4) systematic errors in instrument calibration ($\lesssim$20%, except at field edge; R. Harnden, private communication); and (5) possible systematic effects of interstellar absorption.

The last source of error depends upon uncertainty regarding the amount of X-ray absorbing gas along the line of sight to the cluster; for a number of reasons, we believe the column density of interstellar gas is so small as to have a negligible effect upon the calculated values of L_x. Lyα measurements of the neutral hydrogen density towards α Tau, at a distance of ~20 pc, yield upper limits of $\lesssim$0.2 atoms cm^{-3} (Bohlin, Savage, and Drake 1978). The reddening toward the cluster is very low ($E_{B-V} \lesssim 0.003$ [Allen 1973; Taylor 1980]), suggesting that there are no substantial gas clouds between the Sun and the Hyades. Thus the column density between Earth and the cluster is probably $\lesssim 3 \times 10^{19}$ atoms cm^{-2}, low enough so as not to affect the flux above ~0.15 keV. Also, since the typical neutral gas density within ~100 pc of the Sun has been observed to be extremely low, ~0.1 atom cm^{-3} or lower (Bohlin, Savage, and Drake 1978; Holberg *et al.* 1980), interstellar X-ray absorption is unlikely to affect our results.

In Table 3 we summarize the survey results, indicating the fraction of stars detected in groupings by spectral type and luminosity class, as well as the median L_x for each group.

IV. RESULTS AND ANALYSIS

Inspection of Figure 3 reveals that $\gtrsim$50% of the 93 Hyades in our observing fields have been detected as X-ray sources. In Figure 4 we plot the X-ray luminosities of the detected stars derived using the methods outlined in § III. Since our sensitivity threshold is ~ $10^{28.6}$ ergs s^{-1} at the Hyades distance, it is quite possible that *all* of the Hyades in our fields emit X-rays. Some may simply have lower X-ray luminosities. For example, the Sun, with $L_x \sim 10^{27.5}$ ergs s^{-1} during a typical active phase (Smith and Gottlieb 1974) could not have been detected at the Hyades distance with similar exposure times, unless it were in a flaring state.

Even more remarkable is the fraction ($\gtrsim$80%) of F and G dwarfs that emit X-rays above our detection threshold. Although three of these stars are known spectroscopic binaries (see Table 2), and it is conceivable that there are many undiscovered binaries in the Hyades (Trimble 1980; but see Abt 1980), it is unlikely that mass transfer in close binary systems can account for so many instances of X-ray emission. The evolutionary state of the detected X-ray stars, the range of L_x ($10^{28.5}$–10^{30} ergs s^{-1}), the lack of observable stellar winds, and the high detection rate are conclusive arguments for the ubiquity of stellar coronae in the Hyades.

TABLE 3
SURVEY SUMMARY

	Dwarfs				Giants	White Dwarfs
Parameter	A2–F5	F6–F8	G0–G8	K0 and Later	K0	DA
Detected	9	8	11	17	3	0
Not detected	7	1	2	33	0[1]	2[2]
Median log L_x ...	28.5	28.9	29.1	<28.5	~29.0	<28.5

NOTE.—(1) One giant, ε Tau, not in survey fields. (2) Confirmed Hyades white dwarfs only.

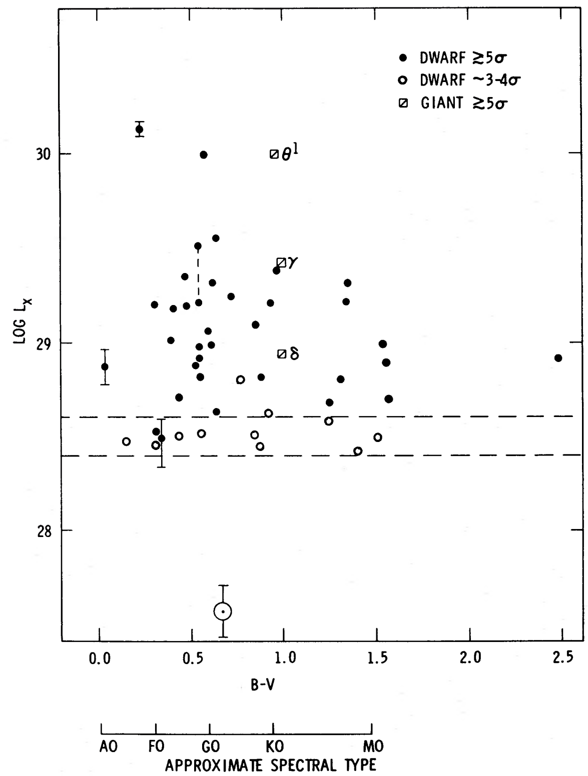

FIG. 4.—X-ray luminosity (0.2–4.0 keV) of stars detected vs. color index. Typical error bars are indicated. The horizontal dashed lines indicate the approximate boundaries of the survey sensitivity limit. The vertical dashed line indicates connects two observations of the same star, BD +14°690, a spectroscopic binary, made 6 months apart. The luminosity of the Sun viewed as a star in the same X-ray band during a typical active phase is indicated.

a) *Range of L_x in Hyades Dwarfs*

Examination of Figure 4 shows there is little apparent change in the range of L_x observed along the Hyades main sequence. Our results, however, are biased by our sensitivity threshold. This is most apparent at the extreme upper and lower ends of the main sequence, where many stars have not been detected in soft X-rays. The median value of log L_x indicated in Table 3 shows that the X-ray luminosity function does change from A to M stars, peaking in the F and G stars, where it is well determined because of the high (≳80%) detection rate. An unexpected result is the wider range of L_x for the extreme upper and lower main sequence stars. In fact, the brightest source in the cluster is 71 Tau, an A8–F0 dwarf (the exact spectrum is probably hard to type because of its extremely rapid rotation: $v \sin i \approx 190$–200 km s^{-1}; Uesugi 1976; Kraft 1965) with $L_x \gtrsim 10^{30}$ ergs s^{-1}. Many K and M dwarfs are undetected, yet some have values of L_x comparable to typical Hyades F and G stars ($\sim 10^{29}$ ergs s^{-1}). Of the K and later type dwarfs, only Hz II 2411, vA 288, vA 305, and vA 351 are known flare stars (Pesch 1968, 1972): vA 288 and vA 351, the only two in our observing fields, were both detected. The significant fraction (≳30%) of K and later type dwarfs showing X-ray emission suggests, however, that flaring is not a likely explanation for the observed X-ray emission (an analysis of time variability is currently in progress and will be reported on in a future paper).

b) *L_x of Giants and White Dwarfs*

Four giants, all of spectral type G9 or K0 III, are members of the Hyades: θ^1, γ, δ, and ε Tau. The first three were located in our observing fields, and all three were detected, though with a range of almost an order of magnitude in L_x (Fig. 4). Baliunas, Hartmann, and Dupree (1980) have reported a correlation of ultraviolet fluxes in the high temperature transition region lines of C IV, Si IV, and N V, the strengths of the emission reversals in the Ca II H and K lines, and the X-ray fluxes observed in the Hyades study. The reality of this correlation will require confirmation from simultaneous optical, UV, and X-ray observations, since variability due to long-term stellar activity cycles could strongly influence the results. Baliunas, Hartmann, and Dupree did not, however, find any evidence of Ca II or ultraviolet variability in the Hyades giants over a 6 month period.

Of the 11 confirmed Hyades white dwarfs (Eggen 1969), two were located in our observing fields, but none were detected above our sensitivity threshold. None of the white dwarfs in our fields has an effective temperature comparable to the high X-ray luminosity white dwarfs HZ 43 or Feige 24 (Lampton *et al.* 1976; Margon *et al.* 1976). Many other white dwarfs which are not Hyades members were also located in our observing fields: upper limits to X-ray emission from these objects will be reported on in a subsequent publication.

c) *Variation of $L_x/L_{\rm bol}$*

The spectral types, luminosity classes, and distances of the Hyades stars are sufficiently well determined to allow us to compute the ratio of X-ray to total stellar luminosity (here labeled $L_x/L_{\rm bol}$, where "bol" refers to bolometric). This ratio is a useful tool for comparison with the predictions of coronal heating theories which depend upon convective motions as the primary energy source. Since in late type stars the energy transport in the region below the photosphere is presumed to be convective, $L_x/L_{\rm bol}$ is thus a measure of the heating "efficiency" for the corona.

In Figure 5 we show the variation of this ratio in several spectral type groups along the main sequence, and for the giants. We have also plotted the range of quiet and active values of $L_x/L_{\rm bol}$ for the Sun. As we move along the main sequence toward later spectral types, there is a clear increase in the maximum value of this parameter. However, as noted before in the case of L_x, the range of L_x/L_{bol} must surely be increasing as most of the K and later type dwarfs are not seen. The range of L_x/L_{bol} in the K and later type dwarfs is probably $\sim\pm 2-3$ orders of magnitude, whereas the G stars have a spread in L_x of only about ± 1 order of magnitude. The low values of L_x/L_{bol} for the giants are in stark contrast to those of the dwarfs, reflecting much lower surface fluxes in these stars.

d) *Comparison with Other Coronal Surveys*

Vaiana *et al.* (1981) have reported on an extensive stellar survey with the *Einstein* Observatory (hereafter referred to as the CFA survey). Their main conclusions are: that stellar coronae are common phenomena in the nearby stars, and probably throughout the Galaxy; that there are large variations (orders of magnitude) of L_x within a given spectral and luminosity class; and that abnormally fast rotators often have enhanced soft X-ray emission compared with more slowly rotating stars. These results extend earlier observations of stellar coronae on rockets and *HEAO 1* (Gorenstein and Tucker 1976; Topka *et al.* 1979; Harnden *et al.* 1977; Walter *et al.* 1980).

At this preliminary stage of the CFA survey, the detected sample of main sequence F stars (15) and G stars (7) is not very large; also, the observational biases are difficult to estimate, since nine of these stars were observed from a preplanned target list, and only selected upper limits are reported. Comparisons with the Hyades survey should therefore be regarded as preliminary. There are, however, indications that the typical X-ray luminosity for F dwarfs in the Hyades and in the CFA survey is about the same: log $L_x \sim 29$. We note that two of the F stars in the CFA survey, HD 28736 and HD 26781, are Hyades members (Pels, Oort and Pels-Kluyver 1975). In Table 4 we list derived X-ray luminosities for these stars as well as for HD 27406, a Hyades member detected fortuitously by Feigelson and De Campli (1980).

The G dwarfs, of which there are more in the Hyades survey (13) than in the CFA survey (7), have apparently

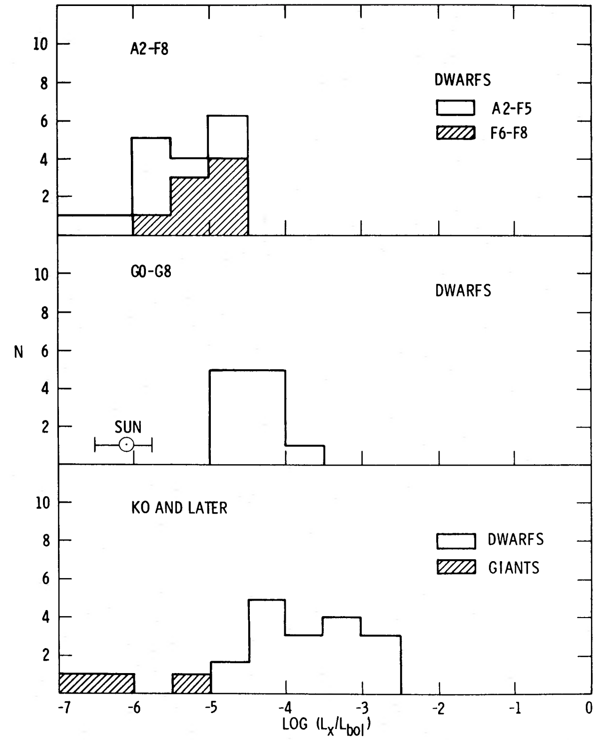

FIG. 5.—Ratio of X-ray to total luminosity for Hyades stars as a function of spectral type for dwarfs and giants.

an order of magnitude lower typical L_x in the CFA survey ($\sim 10^{28}$) than in the Hyades survey ($\sim 10^{29}$). Because of the order of magnitude or more variation in L_x, more data on G stars in the field are clearly needed. If this difference is not an artifact of poor sampling statistics, it could be due to stronger rotational braking in the G and later type dwarfs, resulting in decreased coronal activity for field stars compared to the (younger) Hyades dwarfs (see § VI*b*).

Ku and Chanan (1979) have reported on a survey of the Orion Nebula region with the IPC on *Einstein*. In follow-up observations with the *Einstein* HRI (High Resolution Imager), 120 discrete sources have been de-

TABLE 4

HYADES MEMBERS DETECTED IN OTHER X-RAY SURVEYS

Source[a]	HD	Other Designation	Sp	V	Optical Coordinates (1950)	X-Ray Flux (10^{-13} ergs s^{-1})	Log[b] L_x
V	26781	+10°551	F5	7.1	$4^h11^m49^s$, +10°34′35″	~6	29.1
V	28736	+ 5°674	F3	6.4	$4^h29^m25^s$, +.5°18′15″	~4	29.0
F	27406	+18°623	F8	7.5	$4^h17^m18^s$, +19°06′54″	~3	28.9

[a] V = Vaiana *et al.* 1980; F = Feigelson and DeCampli 1980.
[b] Hyades distance of 45 pc assumed.

tected (Chanan, private communication). The high spatial resolution (2″–5″) of the HRI allows the sources to be identified with main sequence or pre–main sequence stars of spectral types from O to K. The maximum L_x for F and G stars in the Orion region is $\sim 10^{31.5}$ ergs s^{-1}, or about 30 times the maximum L_x observed in the Hyades. The fraction of F and G stars detected above the L_x sensitivity limit of $\sim 10^{30}$ ergs s^{-1} for Orion is ~25–50%, suggesting a significantly higher median L_x than in the Hyades.

V. CONSTRAINTS ON CORONAL PARAMETERS USING SCALING LAWS

In spite of the weak constraints on source spectra discussed previously in § III, it is possible to perform a consistency check of the coronal emission hypothesis using the available luminosity data. Assuming that the emission is from closed loop structures as in the solar corona (Rosner, Tucker, and Vaiana 1978), the X-ray luminosity can be written as:

$$L_x = n^2 \Lambda(T) H(2\pi R^2 \Sigma), \tag{1}$$

where n is the electron density, Λ(T) is the radiative loss function for optically thin emission (computed, e.g., by Cox and Tucker 1969, and by Raymond, Cox, and Smith 1976), H is the scale height of the emitting region, Σ is the fraction of visible disk covered by emitting loops, and R is the stellar radius. If we assume, as in the solar case, that the loop plasma is static, then the following relation should be valid:

$$n^2\Lambda(T) \approx 10^{-6} T^{7/2}/H^2. \tag{2}$$

This relation, the so-called scaling law for coronal loops, has been derived by a number of authors (e.g., Rosner, Tucker, and Vaiana 1978; Vesecky, Antiochos, and Underwood 1979) and basically follows from the requirement that the conductive flux in the loop be dissipated by radiation. The relation is *independent* of the details of the heating mechanism; it should hold for either acoustic or magnetic heating as long as the loop is static.

Another constraint is that the size scale of the emission H be less than or of the order of the gravitational scale height H_g (Vesecky, Antiochos, and Underwood 1978):

$$H \lesssim H_g = 8.26 \times 10^7 T/g, \tag{3}$$

where g is the stellar surface gravity. If the height of the emitting loops is less than H_g, relation (3) clearly follows. If the loop height is much greater than H_g, most of the material will be contained within a few gravitational scale heights, so that (3) still follows.

Combining relations (1)–(3), we obtain limits on the various parameters. For example,

$$T \lesssim T_{max} = \left[\frac{8.26\times 10^{13}}{g\Sigma}\frac{L_x}{2\pi R^2}\right]^{2/5} \tag{4}$$

for a given Σ. Or,

$$\Sigma \lesssim \Sigma_{max} = \frac{8.26\times 10^{13}}{gT^{5/2}}\frac{L_x}{2\pi R^2}, \tag{5}$$

assuming a given temperature. Relations (4) and (5) also set minimum values to the density and pressure, and to the magnetic field needed to confine the plasma inside a loop.

In Figure 6, the values of T_{max} for various values of Σ and for all our sources are shown. Within each luminosity class, dwarfs and giants, the variations in g and R are small compared to the observed variations in L_x, so that T_{max} is essentially a function of Σ and L_x.

The main conclusion that can be drawn from the figure is that all our data are compatible with the stellar corona hypothesis. Even for full coverage of the disk, $\Sigma = 1$, T_{max} is greater than or of the order of 10^6 K for all sources. However, for the low-luminosity dwarfs, full coverage does imply a relatively low T_{max}, especially in view of the fact that L_x is significantly larger than that of the Sun. The average temperature of active region plasma in the Sun is $\sim 3\times 10^6$ K, which implies a coverage Σ of only a few percent, as is observed. If we assume that the temperatures of the Hyades coronae are somewhat higher than that of the Sun, e.g., $T_{max} \gtrsim 5\times 10^6$, then we conclude that for most of our sources, $\Sigma \lesssim 10\%$. This is an interesting conclusion since it implies that variations in the soft X-ray emission should be observed as the star rotates.

VI. DISCUSSION

a) *Coronal Heating: Do Acoustic Models Work?*

Until recently it was generally accepted that the solar corona arose from heating via acoustic waves generated in photospheric motions such as the five-minute oscillation (e.g., Moore and Fung 1972). A number of authors (Ulmschneider 1967; De Loore 1970; Landini and Monsignori-Fossi 1973; Gorenstein and Tucker 1976; Mewe 1979) have extended this theory to predict coronal X-ray fluxes for late-type stars. However, observations of EUV lines formed in the solar transition region indicate that the upward propagating energy flux in acoustic waves fails by several orders of magnitude to account for the observed coronal radiation (Athay and White 1978; Bruner 1979). All of the above models also fail to take into consideration the influence of the stellar

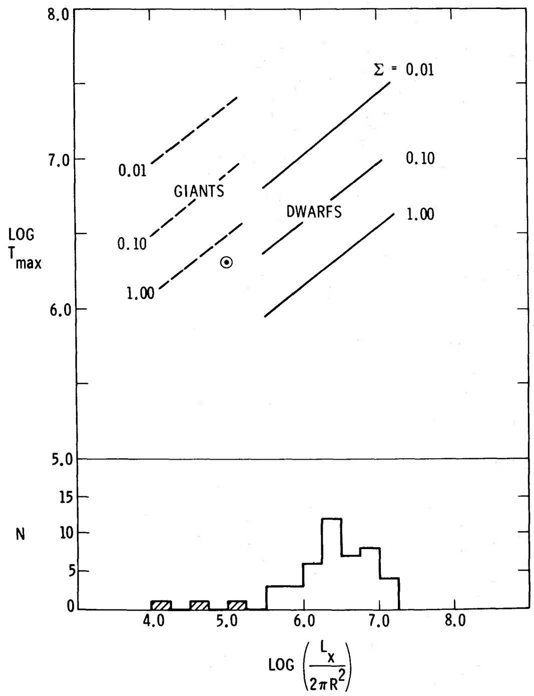

FIG. 6.—Computed values of T_{max} as a function of surface X-ray flux and area coverage factor (Σ). The lower portion of the graph indicates the distribution of the stellar surface X-ray flux (X2) for the Hyades dwarfs (*open histogram*) and giants (*hatched histogram*). The position of the Sun is indicated by ⊙ in the upper portion of the figure, with T_{max} set equal to the observed coronal temperature of $\sim 2 \times 10^6$ K.

magnetic field which, by analogy with the solar corona, must play an important role (see § IV*d*, and Vaiana and Rosner 1978).

Models for stellar coronae which are based on the acoustic wave heating hypothesis, and in particular those which use the minimum flux corona concept of Hearn (1975)—e.g., Mewe (1979)—are in strong disagreement with the X-ray data of both the CFA survey (Vaiana *et al.* 1981) and our results for the Hyades. Some quantitative discrepancies can possibly be reduced: Mewe, for example, calculates X-ray fluxes in the 0.16–0.28 keV band, while the *Einstein* IPC is sensitive out to 4.0 keV; this should, however, make at most a factor of 3 difference in the coronal fluxes between temperatures of $10^6 - 10^7$ K (see Raymond, Cox, and Smith 1976 as a reference for plasma emissivity in various X-ray bands). There is, however, severe *qualitative* disagreement in the prediction of X-ray luminosity along the main sequence. Acoustic heating models predict weak or no emission in early A stars, a peak in emission near F0, with a gradual falloff from F0 to G5 followed by a rapid drop from G5 to K0 (de Loore 1970; Mewe 1979). These predictions follow directly from the requirement that there be a vigorous surface convection region in a star in order for photospheric mass motions to be present, and, consequently, for acoustic waves to be generated. The X-ray surface flux is also predicted to increase rapidly with increasing stellar luminosity (decreasing surface gravity).

When examined in detail, none of the above predictions is confirmed by our data: if the X-ray luminosity function of the Hyades dwarfs peaks at all, it is closer to spectral type G0 than F0; At spectral type K0 and later, where the acoustic flux models predict little or no X-ray flux, about 30% of the dwarfs have X-ray luminosities comparable to the F and G dwarfs—this implies significantly greater surface fluxes than in the earlier type stars, as can be seen in Figure 5; At least one A2 star (68 Tau) has an X-ray luminosity comparable to the F and G dwarfs. The brightest X-ray source in our survey, 71 Tau, while it is of roughly the spectral type predicted to have the largest X-ray flux by acoustic heating theories, is clearly atypical for its spectral class, as can be seen by examination of Figure 3—its strong X-ray emission is possibly the result of its rapid rotation (we note, however, that an undiscovered faint, late type binary companion in a wide orbit may account for X-ray emission in some A star systems). The Hyades giants have roughly the same range of X-ray luminosities as the dwarfs, from which we may infer that their surface fluxes are typically an order of magnitude lower, again in contrast to the predictions of the acoustic heating theories.

The most difficult observation to explain by simple acoustic heating is the median $\log L_x$ for the Hyades G0–G8 dwarfs (~ 29) compared to the Sun (~ 27.5). The Hyades dwarfs appear to be quite similar to the Sun in temperature and luminosity, and perhaps slightly more metal rich (see § VI*b*). Clearly, other characteristics of the solar type Hyades (which are not included in simple acoustic heating theories) must be considered before we can understand the X-ray emission in these stars.

b) *Rotation and Stellar Activity in the Hyades and Other Main Sequence Stars*

Wilson (1966), Kraft (1967), and Skumanich (1972) have demonstrated a strong correlation of chromospheric activity (as measured by emission reversals in the cores of Ca II H and K) with main sequence age for solar type stars. Skumanich has suggested a $\sim \tau^{-1/2}$ law for such emission; this same law also appears to hold for rotation on the main sequence (Skumanich 1972; Smith 1979; Soderblom 1980), although Smith and Soderblom disagree as to whether or not the Sun obeys this scaling law. Skumanich (1979), Walter and Bowyer (1981), Walter (1981), and Ayres and Linsky (1980) have suggested a similar correlation between X-ray luminosity (L_x) or the parameter L_x/L_{bol} and the stellar equatorial rotational velocity v_e or angular velocity Ω. Skumanich suggests a quadratic dependence of L_x with Ω for late type single main sequence stars and a linear dependence for spectroscopic binaries, based upon a small sample of stars observed on *HEAO 1*. Walter (1981) and Walter and Bowyer (1981) suggest a linear dependence for both RS CVn binaries and late F–G stars for $L_x/L_{\rm bol}$ versus Ω. Ayres and Linsky note a strong correlation of $L_x/L_{\rm bol}$ versus v_e, declining to propose a particular functional form, although their compilation of data suggests a quadratic dependence.

The sample of solar-type (G0–G8) Hyads we have detected in soft X-rays is large enough (11) and complete enough (~85% detection rate) that sample averages should be characteristic for the cluster as a whole. The stellar rotational velocity data for these stars are not, however, complete. Values of $v \sin i$ have been measured for seven of the solar type dwarfs detected in soft X-rays, mostly of spectral type G0–G2 (Kraft 1965; Soderblom 1980). The average $v \sin i$ from these studies are ~11 km s^{-1} and 7 km s^{-1}, respectively.

The decrease in v_e with spectral type (Kraft 1967) suggests that we may use these numbers as upper limits if we include stars of later spectral type than G2. Correcting by the factor $4/\pi$ for random spin axis orientations, we find that $v_e \lesssim 9$–14 km s^{-1} for the solar-type Hyades. Using the average values of $L_x/L_{\rm bol}$ for the Sun (~10^{-6}; see § IV and Ayres and Linsky 1980) and solar type Hyades derived in § IV, the ratio of this parameter for the Hyades relative to the Sun is at least 30. The equatorial rotation velocity of the Sun is 2.1 km s^{-1} (Allen 1973). Thus, if we seek a simple dependence of $L_x/L_{\rm bol}$ upon v_e (or in our case, Ω, since the stellar radii are presumed roughly equal), our data suggest a quadratic rather than a linear dependence.

The apparent discrepancy between our results and those of Walter (1981) may be due to a number of observational causes: the inclusion in Walter's sample of stars from spectral type F8–K5, only seven of which are single stars, the use of X-ray data from a number of different instruments (*HEAO 1*) A-2 Low Energy Detectors, *Einstein* IPC, and HRI) with differing low energy cutoffs in the $\frac{1}{4}$ keV band, and a particularly high value of $L_x/L_{\rm bol}$ for the Sun (10^{-6}–10^{-5}). In this regard, the Hyades survey data are internally self-consistent in that they all are from the *Einstein* IPC, and the stars considered are all of the same approximate spectral and luminosity class. The point chosen for the solar X-ray luminosity (~$10^{27.5}$) is actually conservative, in that it is the measured value for the Sun in a moderately active state taken from Smith and Gottlieb (1974). These and other possibly unknown observational effects may allow both results to be reconciled at some later date.

The high ($\gtrsim 10^{30}$ ergs s^{-1}) median L_x for F and G stars in the Orion Nebula region (see § V) also suggests a correlation of stellar activity with age. X-ray surveys of the Pleiades and the Ursa Major group are currently under way (D. Helfand, J. Linsky, private communications); these observations will be quite useful in pinning down the functional form of the (L_x, main sequence age, rotation)-relation.

c) *The Influence of Other Stellar Parameters on Soft X-ray Emission in the Hyades Dwarfs*

Could other properties of the Hyades stars besides age or rotation produce the difference in L_x between the solar type Hyades and the Sun?

There exists a long standing discrepancy between spectroscopic and photometric measures of the Hyades metal abundance (Nissen 1980; Flower 1980). Hardorp (1980*a*) has suggested a resolution of the disagreement in favor of a solar metal abundance. In fact, one of the G stars in our survey (HD 28099, $L_x \sim 10^{29.6}$ ergs s^{-1}) is suggested by Hardorp (1980*b*) as a "perfect" solar spectral analog with respect to its line spectrum and energy distribution, even though it is of somewhat later spectral type (G6 V) than the Sun. Conversely, the absolute visual magnitude and $B-V$ color index of the Sun would place it right on the Hyades main sequence, if we use the most recent distance modulus determination of Hanson (1980; $m-M=3.30$). While more recent work (Twarog 1981, Branch, Lambert and Tompkin 1980) suggests that the Hyades are slightly metal-rich, it is unlikely that we can account for the difference in X-ray emission between the Sun and the Hyades G stars in terms of elemental abundances influencing the mechanical energy generated in photospheric motions.

The detailed properties of the stellar convection zone may also influence coronal heating (Linsky 1980*b*). The Hyades G0–G8 dwarfs should have solar-like convection zones, if we neglect the effects of rotation; numerical simulations of the solar convection zone do, however, indicate that rotation may have a significant effect on its depth (Gilman 1979, Glatzmeier 1980). Because of their complexity and the detailed calculations entailed to apply them to the Hyades, a discussion of such models is clearly beyond the scope of this paper. We note, however, that any dependence of the properties of the convection zone on rotation will be implicitly included in any rotational scaling law formulation (see (*d*) below).

d) *Magnetic Heating Models and the Solar Analogy*

Because of the mounting evidence from solar and stellar observations cited above that acoustic heating models, at least in their present form, are no longer tenable, it is now widely believed that some form of magnetic dissipation must be responsible for coronal heating. Two general types of mechanisms have been suggested for such heating, loosely labeled wave dissipation and current dissipation. In the wave mechanism, the energy is generated by photospheric motions and then propagated up to the corona in the form of Alfvén waves (Wentzel 1976, 1977, 1979; Ionson 1978; Hollweg 1978). In the current mechanism, the coronal field is postulated to be stressed, due either to the winding of field lines by photospheric motions or to the emergence from the photosphere of new flux in an already twisted state. If the stresses are sufficiently large, the resulting narrow current layers can dissipate rapidly by some anomalous resistivity such as that caused by ion-acoustic or ion-cyclotron turbulence (Rosner, Tucker, and Vaiana 1978; Sturrock and Uchida 1980).

It is important to note that just as in the case for acoustic heating, photospheric motions are *necessary* for magnetic heating. In both models, the power source for the heating is mass motion at the stellar surface. Standard theory also predicts that convection or some other type of nonsteady motion is necessary to generate surface magnetic fields. For example, the solar field is believed to be due to a dynamo process involving the interaction of differential rotation and surface convection (Leighton 1969; Parker 1979). Differential rotation, by itself, cannot maintain a magnetic field (Cowling 1934), and cannot account for solar activity (Parker 1970). In fact, the basic mechanisms proposed for producing and sustaining the solar differential rotation all require the presence of surface convection (Tassoul 1978).

Since models for the formation and heating of stellar coronae are in a primitive state (see, e.g., Linsky 1980*b*), it is not possible at present to predict on theoretical grounds any simple scaling relation between X-ray luminosity and stellar rotational velocity. However, certain features of the formation of the solar corona appear to be well understood. In virtually all models of the solar dynamo (e.g., Babcock 1961; Leighton 1969; Parker 1970; Yoshimura 1975) the coronal magnetic field is believed to be primarily toroidal and is generated from a poloidal seed field via differential rotation in both latitude and radius. The toroidal field is produced in the convection region below the photosphere. Once a critical magnitude for the field is reached ($B_c \sim 200$ gauss estimated for the Sun), magnetic buoyancy causes it to erupt into the corona, giving rise to sunspots, active regions, etc. It is important to note that the rate of generation of magnetic energy in this process is more than sufficient to power the (solar) coronal X-ray losses. The total amount of toroidal magnetic field energy generated in one solar cycle is $\sim 10^{36}$ ergs (Parker 1970), which yields a time-averaged luminosity of $\sim 10^{27.5}$ ergs s^{-1}; wavelike mechanisms such as those described above may also contribute significantly to the coronal heating.

If a dynamo process similar to that postulated for the Sun does occur in the Hyades G stars, then one can expect a coronal heating rate, and hence, any X-ray luminosity of at least

$$L_x \sim \frac{B_c^2}{8\pi} \frac{V}{\tau_c},$$

where B_c is the critical field strength described above, V is the volume over which the field is formed, and τ_c is a stellar cycle time analogous to the 11-year solar cycle.

The parameters V and τ_c depend primarily on the properties of the differential rotation, $\Omega(r, \theta)$. V is determined by the depth of the differential rotation; τ_c, which is essentially the time required for the differential rotation to amplify the toroidal field to the value B_c, is determined by the magnitudes of $d\Omega/dr$ and $d\Omega/d\theta$ (Parker 1979). Lacking a generally accepted theory of stellar differential rotation (Tassoul 1978), we simply assume that the *form* of $\Omega(r, \theta)$ in the Hyades G stars is the same as in the Sun. In this case we expect that V is independent of v_e, but that τ_c is proportional to v_e. Based on this assumption, we conclude that $L_x \propto B_c^2 v_e$.

The key unknown is the dependence of B_c on v_e. In the case of the Sun, B_c is empirically determined from estimates of the observed magnetic flux emerging from the photosphere in one solar cycle (Babcock 1961). Since the typical magnetic field in the Hyades G stars is not known, we cannot empirically prescribe the value of B_c for these stars. In general, we expect it to be larger for a larger rotation rate (shorter cycle), but the exact dependence can only be given by a complete dynamo model, which is not yet available.

Hence, all that we can conclude is that L_x has a higher dependence on v_e than linear, and which may be compatible with a quadratic scaling law, as our data suggest. We note also that there is no reason to expect, *a priori*, the same dependence of B_c on v_e for stars of widely different spectral type or luminosity class, since the value of B_c is likely to depend upon the characteristics of the convection zone. Thus L_x may well scale in a different manner for dwarfs and giants; many more observations will be required to clarify the nature of any such scaling relations.

VII. SUMMARY AND CONCLUSIONS

The results of the preceding sections may be summarized as follows:

1. Stellar coronae are common among the Hyades stars, with observed X-ray luminosities (0.2–4.0 keV) of $\sim 10^{28.6}-10^{30}$ ergs s^{-1} in 50% of the stars in the cluster center and indications that most, if not all, of the Hyades have X-ray emitting coronae at some level.

2. The X-ray luminosity function for F and G dwarfs in the Hyades is well determined, with median values of $L_x \sim 10^{29}$ ergs s^{-1} for both spectral classes, and a spread in X-ray luminosity of about an order of magnitude.

3. Acoustic heating models fail to predict the observed X-ray fluxes in either a qualitative or a quantitative fashion.

4. For a sample of 13 Hyades dwarfs of spectral type G0–G8, the X-ray luminosity is ~30 times that of the Sun, and appears to require a quadratic dependence of L_x or L_x/L_{bol} on v_e or Ω, if such simple scaling laws are assumed to hold.

The observations we have discussed so far have raised far more questions than they have answered. In particular: What are the temperatures of these coronae? Are they variable over a large range of time scales, such as in the Sun, and what can we infer from such variability observations about the geometric structure of the coronae? How do the X-ray observations relate to those in visible and ultraviolet light?

In an attempt to answer some of these questions, we are currently conducting a follow-up series of observations with *Einstein* to better determine spectral and temporal parameters for selected stars; in addition, Zolcinski *et al.* (1981) have observed a number of the Hyades dwarfs with the *International Ultraviolet Explorer*, and are currently analyzing the data from these observations. Other observations in X-rays and visible light are also planned. It is only by such intensive studies that we may be able to determine the true functional dependence of the coronal heating on stellar parameters, and to better understand the place of the solar corona in relation to other stellar coronae.

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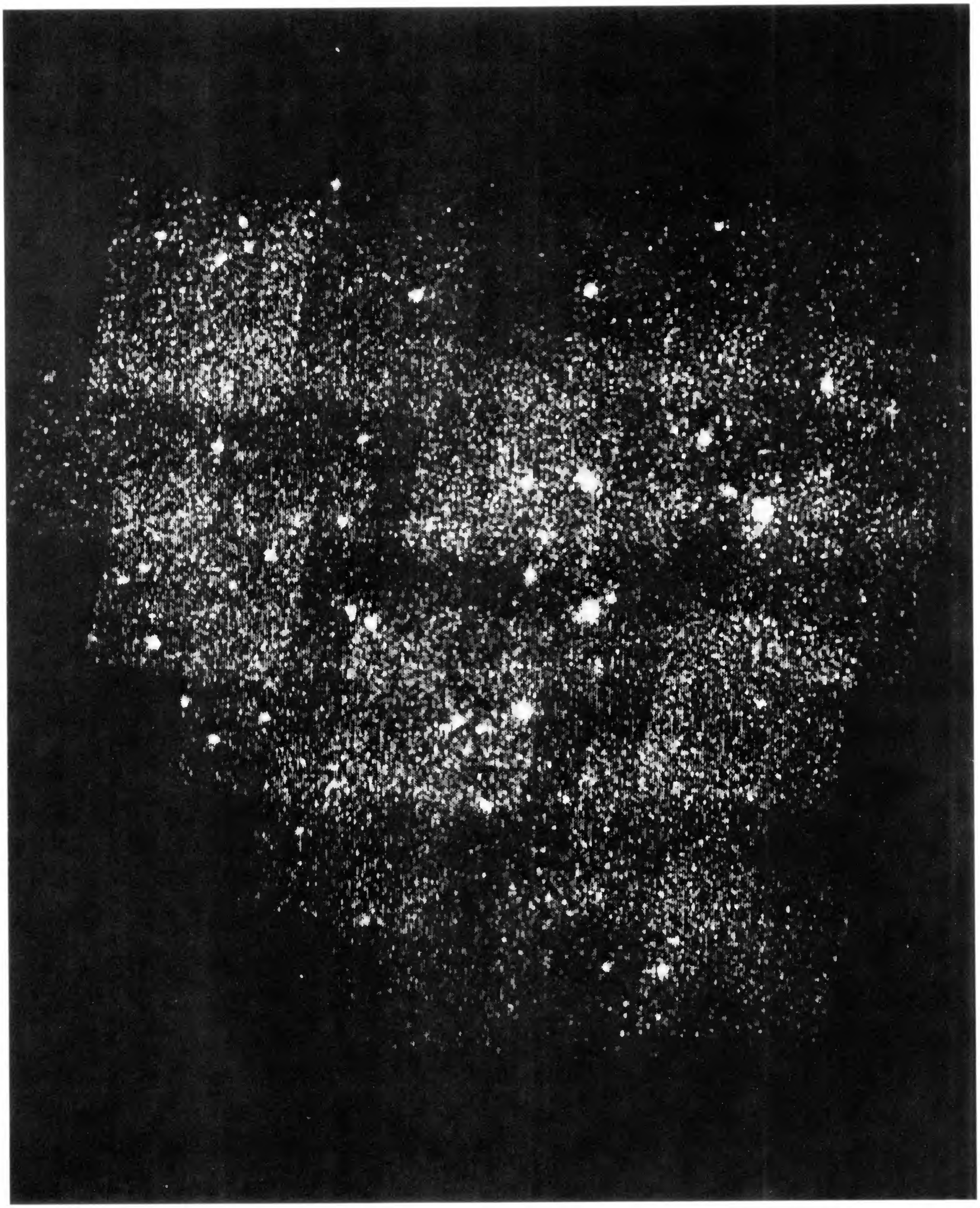

FIG. 2.—Composite image of 27 X-ray fields in survey

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