A 1.5 GHz RADIO SURVEY OF THE HYADES OPEN STELLAR CLUSTER

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ABSTRACT

We report the results of a radio survey of the Hyades open stellar cluster carried out with the Very Large Array at 1.5 GHz. Seventeen fields containing over 150 catalogued stars were mapped down to a limiting sensitivity ranging from 0.3 mJy at the centers of the fields to 0.9 mJy at a distance of 20′ from field centers. Only two stars were detected as radio sources: the evolved spectroscopic binary V471 Tau, consisting of a white dwarf and a red dwarf; and the apparently pre-main-sequence G+K star spectroscopic binary HD 27130. The lack of detection of any single stars in the Hyades is consistent with other observations showing that most dwarf stars are no longer active by the time they reach the age of the Hyades, presumably because they have spun down. However, the Hyades is known to contain a number of late-type M dwarf stars which are of age similar to the nearby population of flare stars and rotating at least as rapidly as them. The nearby population would be detectable at 1.5 GHz at the distance of the Hyades, and based on reasonable assumptions about the number of flare stars in the Hyades, we might expect to have seen several highly-polarized flares if the Hyades M dwarfs are as active at radio wavelengths as the nearby flare stars.

1. INTRODUCTION

Since the Sun would not be detectable as a radio source if it lay at the distance of the nearest stars, the detection of an ever-increasing number of late-type stars as steady radio sources poses a challenge to our understanding of stellar activity. The reason that these stars can be detected is that they possess a nonthermal corona, in addition to the thermal corona like the Sun's (albeit hotter) revealed by x-ray observations.

The classes of stars which show radio activity tend to be the same classes which display other forms of enhanced activity attributed to the presence of stellar magnetic fields. That is, they are the same classes which have strong soft x-ray emission, x-ray flares, optical/ultraviolet flares, and evidence for a chromosphere. The common interpretation of the different activity properties of different populations of similar stellar types is that the more active stars are more rapidly rotating, and that this rapid rotation leads to enhanced solar-like dynamo action which generates magnetic fields. The explosive release of free energy stored in complex field configurations can explain stellar flares, and possibly also the nonthermal heating required to maintain the chromospheres, thermal (x-ray-emitting) coronae and nonthermal (radio-emitting) coronae of these stars.

The age of a single star is thought to be a major factor in determining its rotation rate. The general scenario is that when stars first arrive on the main sequence they tend to be rapidly rotating because of conservation of angular momentum as they collapse from a slowly-rotating gas cloud. The rotation energy can be used to drive the various forms of magnetic activity. One such form will be a stellar wind, and strong magnetic fields in the corona maintain the wind corotating with the star out to a considerable distance above the photosphere. The wind thus has a higher specific angular momentum than photospheric material, and hence carries angular momentum away from the star. As a star ages it slows down because its angular momentum is effectively carried away by the stellar wind ("magnetic braking", Schatzmann 1962). Studies of rotation amongst members of young open stellar clusters (reviewed by Stauffer 1987, 1991) have provided support for this picture, and suggested that earlier stellar types spin down faster: thus α Per (age $\sim$30 million years) contains rapidly-rotating G dwarfs whereas the Pleiades ($\sim$50 million years) has none, but the Pleiades does contain rapidly-rotating K dwarfs which the Hyades ($\sim$600 million years) lacks; the Hyades does contain rapidly-rotating late-type M dwarfs.

While the nonthermal radio activity of stars presumably results from the same general mechanism (dynamo-induced magnetic activity) as the other forms of stellar activity, its generation must differ in detail, since it alone requires nonthermal acceleration of particles, rather than a heating mechanism as is implied for the other forms of activity. Therefore radio emission serves as a diagnostic of stellar activity different from other wavelength ranges, and it is important to determine its relationship with rotation and with age.

A convenient way of studying the dependence of radio emission on age is to carry out wide-field surveys of open clusters of known age for which the membership has been well-studied. Numerous stars can be observed simultaneously, which increases the chance of having a flaring star in the field of view and compensates a little for the fact that the large distance to the cluster means that only the largest flares can be detected. Bastian *et al.* (1988) discuss wide-field mapping in their survey of the Pleiades cluster, at a distance of 125 pc and an age of 70 million yr. None of the many Pleiades flare stars observed were detected; the only

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possible detections were two G stars which are probably foreground sources and therefore not cluster members.

In this paper we report the results of a similar survey of the older (800 million yr) but closer (45 pc) Hyades cluster. The closeness of the Hyades allows us to reach a much lower luminosity threshold than can be achieved for the Pleiades. We do not find any of the single stars in this cluster to be radio sources; the only confirmed radio detections are two well-known active binary systems. Two previous complementary radio surveys of the Hyades (a low-sensitivity survey of 320 sources by Crain *et al.* 1986, and a targeted survey of a small number of x-ray-selected M dwarfs by Caillault 1989), both at 5 GHz, between them detected one of these two binaries and no other candidates. In the following sections we will discuss the survey and the detected stars, and proceed to discuss the dependence of stellar radio activity on age.

2. OBSERVATIONS

The observations were carried out at 1.5 GHz with the Very Large Array[1] (VLA) on 19, 24, and 30 September, 1986. In total, the observations lasted 14 h and were spread over several days in order to search for time variability in any detected sources. The first two observations were carried out during the move from "B" to "C" configuration, while the third was in "C" configuration. All observations were in the 1.5 GHz band: two sidebands (1422.6 and 1522.6 MHz) were received and were combined in the analysis (wide frequency separation of the sidebands improves the u,v coverage of the observations somewhat). A narrow bandwidth (12.5 MHz) was used in order to reduce the effects of bandwidth smearing in wide-field mapping; this technique is thoroughly discussed by Bastian *et al.* (1988) and we will not repeat the discussion here. Typical integration times were about 40 min per field. Self-calibration was used extensively to improve the maps, and the final maps used for the survey all had the same detection threshold ($3\sigma \approx 0.3$ mJy) to within 20%, despite a range from 0.06 to 1.1 Jy in the total fluxes in each field. The final noise level was close to the theoretically expected value of about 0.08 mJy (40 min integration with 25 MHz total bandwidth). Two interesting extended radio galaxies detected during this survey will be discussed briefly elsewhere (White *et al.* 1992b).

The Hyades open cluster covers an area on the sky approximately 20° across, which is too large to be surveyed in full. We therefore chose 17 fields centered on interesting Hyads. With 14 of the fields we covered about 20% of the central 4°×4° portion of the cluster, centered at RA =04h22m, dec.= +16°. These fields were centered on the four K giant members of the Hyades (HD 27371, HD 27697, HD 28307, and HD 28305; HD 27697 is a spectroscopic binary of period 8 days with a K0 III primary); the short-period spectroscopic binaries HD 27130 (G6 primary, period 5.6 days), HD 27628 (A3, 2 days), HD 27691 (F8IV+G0, 4 days), and HD 27749 (A2, 8 days); the G1V main-sequence star HD 27836, which is 10^3 times more luminous as an x-ray source than the Sun; the white dwarf/M dwarf binary HZ 9; and the late-type dwarf stars vA 276, vA 334, vA 351, and vA 500, all of which have been detected as x-ray sources. The three additional fields contain the eclipsing white dwarf/K dwarf binary V471 Tau (period 0.5 days), and the probable low-mass flare stars Johnson 331 and LP 358-250. The coordinates of the 17 fields observed in the survey, together with the names of the primary stellar target in each field, the map rms in the total intensity maps (which was in all cases similar to the rms in the circular polarization maps), and the total cleaned flux in the final total intensity map, are given in Table 1. The final column lists the number of catalogued objects within 20′ of field center (see below): all are listed as stars in the SIMBAD database (there is also some overlap between fields). For each field a 1024×1024 pixel map with a cell size of 2.7″ or 2.8″ was made. The primary beam of the VLA has a full width at half maximum (FWHM) of about 32′ at 1.5 GHz, so the maps extend out to beyond the FWHM: this allowed us to clean a number of confusing sources far from the field centers. Natural weighting was used in gridding the visibilities. The synthesized clean beam obtained was nearly circular with a diameter of 13″–15″, allowing position measurements accurate to better than 1″ in most cases.

TABLE 1. Observed fields in the Hyades cluster (equinox 1950.0).

Field	Hyad	RA	Dec.	I map rms (mJy)	Cleaned flux (mJy)	Catalogued objects
1	V471 Tau	03 47 21.0	+17 06 18.0	0.11	614	4
2	HD 27130	04 14 24.0	+16 45 00.0	0.09	83	16
3	HD 27371	04 16 57.0	+15 30 00.0	0.09	360	3
4	HD 27628	04 19 14.0	+13 57 38.0	0.10	1040	7
5	HD 27691	04 19 54.0	+14 56 25.0	0.10	297	15
6	HD 27697	04 20 03.0	+17 25 37.0	0.10	152	13
7	HD 27749	04 20 18.0	+16 45 00.0	0.09	97	9
8	vA 276	04 20 35.0	+15 38 42.0	0.09	360	13
9	HD 27836	04 21 12.0	+14 43 30.0	0.10	440	8
10	vA 334	04 21 54.0	+15 45 30.0	0.09	174	12
11	vA 351	04 22 21.0	+17 09 06.0	0.09	167	14
12	LP 358250	04 23 45.0	+24 50 18.0	0.08	69	4
13	HD 28307	04 25 12.0	+15 51 00.0	0.08	199	9
14	HD 28305	04 25 42.0	+19 04 16.0	0.09	235	3
15	vA 500	04 26 06.0	+16 08 00.0	0.09	278	17
16	HZ 9	04 29 12.0	+17 37 30.0	0.10	486	24
17	J 331	04 45 08.0	+16 58 06.0	0.09	467	10

3. ANALYSIS

The positions of all sources in excess of 0.4 mJy (about 4σ) in each of the 17 maps were measured. No primary beam correction was used during this stage of source identification, so the true fluxes of identified sources further than 10′ from field centers were considerably more than 0.4 mJy. This produced a list of 440 radio sources. Because of the lack of a primary beam correction this is not a flux-limited sample: however, our purpose here is to measure the radio fluxes of known stars rather than identify radio sources, and the approach we use gives us more sources than would a flux-limited sample.

Next we searched the astronomical data base SIMBAD maintained by CDS (Strasbourg, France) for all known

[1]The Very Large Array is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation

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catalogued objects in the fields up to 20′ from field center. This data base contains most of the catalogues of Hyades members, including the van Bueren (1952), van Altena (1969), and Pels *et al.* (1975) catalogues. The resulting list contained 155 different objects, all of them stars (excluding an entry for the Hyades cluster itself). We compared the positions of the objects in this list with the list of radio source positions. We also checked the locations in the radio images of all catalogued stars with positions known to better than about 15″ (the beam size) in case there were 3σ sources present. Both techniques produced only two matches, both spectroscopic binaries: the DA+dKe binary V471 Tau (radio flux of 0.4 mJy), and the G6V+K6V binary HD 27130 (radio flux of 0.5 mJy). The measured radio position of V471 Tau was $03^h47^m\ 33\overset{s}{.}8 \pm 0\overset{s}{.}1$, $+17°05'43'' \pm 1''$ (equinox 1950.0, epoch 1986.7), compared with the optical position of $03^h47^m\ 33\overset{s}{.}8 \pm 0\overset{s}{.}1$, $+17°05'45'' \pm 1''$ (Crain *et al.* 1986; uncorrected for proper motion, which has not been measured). The measured radio position of HD 27130 was $04^h14^m\ 46\overset{s}{.}9 \pm 0\overset{s}{.}1$, $+16°49'34'' \pm 1''$, compared with the SAO optical position of $04^h14^m\ 46\overset{s}{.}84 \pm 0\overset{s}{.}01$, $+16°49'34\overset{''}{.}2 \pm 0\overset{''}{.}2$ (corrected for proper motion).

For completeness, Table 2 presents a list of the stars within 20′ of a VLA pointing center, ordered by right ascension. Stellar properties listed are taken directly from the SIMBAD database, supplemented in places with information from Micela *et al.* (1988). The first column in this table gives the star name; the second column lists a selection of alternate names from the SIMBAD database; the third column gives the spectral type; and the fourth column indicates whether the star is a spectroscopic binary ("SB") or a known x-ray source ("X"; Micela *et al.* 1988). The Taurus–Aurigae star-forming region lies in the direction of (but well beyond) the Hyades, and a number of pre-main-sequence stars also fall in these fields. These are indicated by the notations "CTT" (for a classical T Tauri star) and "WTT" (for a weak-line T Tauri star) in the fourth column. If an asterisk precedes the name of the star then it is believed to be a Hyad; if the star name is italicized, the star lies within 10′ of a VLA pointing center. The flux upper limits can be taken to be 0.3 mJy (3σ) for all undetected sources within 8′ of a field center (i.e., those italicized in Table 2), while for those sources further out the primary beam correction elevates the detection limits to, e.g., 0.4 mJy at 10′ and 0.9 mJy at 20′.

We also looked for circular polarization in the fields. A typical VLA field at 1.5 GHz contains many extragalactic sources, but none of them have any significant circular polarization. Active stars are virtually the only class of radio sources known to have high degrees of circular polarization, and thus in principle any strongly circularly polarized sources are likely to be stellar radio sources. This provides a potentially powerful technique for identifying stars among the many background sources in a field. However, for this task wide-field mapping with the VLA has the major shortcoming that the feeds of the VLA are circularly polarized and the two circular polarizations effectively point at slightly different locations on the sky ("beam squint"). In the central portion of the primary beam this is not important because the two polarizations have essentially the same response; however, at the edge of the primary beam pattern of the antenna the two polarizations can have very different responses with the result that an intrinsically unpolarized source may appear to be polarized.

To estimate the effect of "beam squint" on these observations we took all the sources above 0.3 mJy (22 in total) in the circular-polarization maps (Stokes V) and studied the distribution of the degree of circular polarization as a function of position angle and distance from the pointing

TABLE 2. Stars in the observed fields of the Hyades cluster.

Star	Other names	Type	Note
HD 24040		G0	
AG+16 327		K0	
* *V471 Tau*	BD+16 516,	dA+	
	WD 0347+17	K0V	SB,X
BD+17 639		K4	
vA 83			
HD 285573		K2	
HD 285562		A2	
HD 285574		F5	
* *vA 94*	LP 414-148		
* *vA 95*		M	
HD 285677		K5	
HD 285687		G0	
LP 414-201			
HD 27110	AG+16 358	F2V	
HD 285678		A7	
* *HD 27130*	vB 22, V818 Tau,	G6V +	
	AG+16 359, vA 108	K6V	SB
HD 285686		A5	
NTTS			
041529+1652			WTT
HD 285693		G5	
* *HD 27771*	vB 28, 54 γ Tau,		
	vA 175	K0III	SB,X
HD 285692		G0	
vA 217			
HD 285737		F5	
BD+13 668B			
BD+13 668C			
* *HD 27628*	vB 38, vA 229,		SB,X,
	60 Tau, V775 Tau	A3m	δ Scu
HD 285757		F5	
HD 285736		G0	
HD 285758		F8	
HD 285735	BD+16 583	K2	
HD 285756		F2	
LP 415-366	GH7-178		
HD 286731	BD+13 669	G5	
* vA 241		M	
HD 27686	AG+14 391	G5	
HD 286732	BD+13 670	K5	
vA 247	LP 475-319		
HD 27684	AG+17 383	F7V	
* *vB 39*	HD 27685, vA 248,		
	AG+16 363	G4V	X
* *HD 27691*	vA 249, LP 415-794,	F8IV+	
	vB 40, AG+14 392	G0	SB,X
vB 1250			
BD+17 712B			
HD 285734		K5	
* *HD 27697*	vB 41, vA 256,		
	61 δ Tau	K0III	SB,X
HD 285759		A7	
HD 285811		A1	
* vB 57	HD 27991, vA 360,		
	70 Tau, HR 1391	F7V	X
HD 28007	BD+17 722	F2V	
HD 28008	vA 369	G5	
vA 380			
* vA 382	HG 7-218, LP 415-82		X
V823 Tau			
HD 28085	BD+16 600	G8II	
* *LP 958-250*			
IRAS			
04239+2436			
HD 28170	BD+24 658	A1III	
HD 285813		G0	
AG+15 367	vA 449, HD 285808,		
	BD+15 626	F5	
vA 451	LP 415-113		
HD 285807		G0	
AG+18 340	HD 285765, G 7 -227		
	BD+18 638,	K0	
DC 10505	HD 28236, W Tau		
	IRAS 04250+1555	M6	
* vA 475	vB 189, HD 285804	K5	
HD 28893	BD+15 630	K2	
BD+18 640B			
HD 28292	75 Tau, HR 1407,		
	BD+16 605	K2III	
* *HD 28905*	vB 70, HR 1409,		
	74 ε Tau	G9.5III	
* *HD 28907*	vB 71, 77 θ^1 Tau,		
	BD+15 631	K0IIIb	SB,X
* vB 72	78 θ^2 Tau, HD 28319,		
	HR 1412, vA 491	A7III	SB,X
* *vA 500*	vB 190	K8V	X
HD 285806	V994 Tau	K7	
UBV 21153			
* vA 502		K7Ve	
G 7-40			
* *vB 75*	HD 28363, vA 511,	F7V+	
	BD+15 633	G0V	X
* vA 260	LP 415-367	M6	
HD 285729		G5	
* *vA 262*	LP 415-35	M8	
HD 285738		F5	
HD 285755		F8	
* *HD 27749*	vB 45, vA 272,		
	63 Tau, AG+16 364	A1m	SB,X
* *vA 276*	vB 173, HD 285749,		
	V989 Tau, AG+15 359	K0V	X
HD 27761	AG+16 365	A0V	
HD 285739		K0	
* vB 46	HD 27771, vA 279,		
	AG+14 393	G5V	X
HD 285751		G5	
HD 285746	BD+15 617	G0	
* *vA 282*		M2	
HD 285724		G0	
* *vA 288*		M2.5e	X
BD+17 714B			
AG+15 360	HD 285748	F5	
HD 285731		K2	
* vA 297		M2	
AG+15 361	HD 285752	F8	
IN Tau		M3e	CTT
HD 285728		F8	
AG+17 385	HD 285727	G5	
HD 285753		G5	
* vB 47	HD 27819, 64 Tau,		
	vA 301, AG+17 386	A7V	SB,X
HD 285754		F8	
* *HD 27836*	vB 50, V895 Tau,		
	vA 308, AG+14 395	G1V	X
HD 285726		F5	
HD 285740		G0	
IO Tau		M	CTT
* vB 51	HD 27848, vA 315,		
	AG+16 368	F8V	
AG+17 387	HD 285729	K2	
HD 27849	AG+14 396	A	
HD 285760		K0	
HD 27859	vB 52, vA 319	G2V	
* *vA 321*	LP 415-59	M2	
* *vA 329*			
HD 285741		G8	
G 7-37			
HD 285747		K5	
HD 285745		F8	
* *vA 334*		K7	X
HD 285730		G5	
* vA 342	HD 285742, V991 Tau,		
	BD+16 593	K4V	
* *vA 351*		M2	X
BD+15 621B			
* *vA 518*		M1.5	X
* *vA 348*	BD+15 634, vB 181,		
	HD 285805	K5V	X
HD 285803	BD+16 607	K5	
HD 285869		A3	
HD 28484	BD+15 635	M3	
HD 28605	vA 612, BD+17 741	K2	
* *vA 622*	HD 285849	K7V	
V718 Tau	IRAS 04284+1732	Ce	
GCRV 55163			
IRAS			
04286+1749			
HD 285855		G0	
* *vA 627*	HD 28634, PELS 63,		
	BD+17 744	K2	X
vA 657	LP 415-187		
L1551-51	NTTS 042916+1751	K7	WTT
HD 285850		F3	
V826 Tau	HBC 400	K7	WTT
* *HZ 9*	vA 673, LEID 70,	dAe+	
	LP 415-186	dM4.5e	SB,X
* vA 674		K9	X
AS 83			CTT?
GG Tau	IRAS 04296+1725	K6Ve	CTT
HD 28762	BD+17 747	F8	
HD 285851	BD+17 748	G6	
HD 285853		F5	
HD 285852		G7	
TAP 48			WTT
DQ Tau	IRAS 04439+1654	M0Ve	CTT
V1001 Tau	IRAS 04441+1657,		
	Haro 6-37	K6	CTT
DR Tau	IRAS 04442+1653	K4Ve	CTT
LP 416-549			
HD 286029		G5	
* *J 391*	LEID 95		
HD 286030	BD+16 652	F0	
HD 286080		G5	
HD 286073		F0	

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center. A clear pattern of circular polarization increasing with distance from the pointing center, and highest on a line running diagonally across each map from the top left to the bottom right, was apparent, which we attribute to the effect of beam squint. None of the catalogued stars coincided with a circularly-polarized source, and none of the circularly-polarized sources were sufficiently discordant from the beam-squint pattern to believe their polarization to be intrinsic, which might mean that they were uncatalogued stellar sources. Thus we believe that no circularly-polarized sources were detected in this survey, with an upper limit of about 0.3 mJy in Stokes V.

4. THE DETECTED STARS

4.1. V471 Tau

V471 Tau is well-known to be one of the most active stars in the Hyades cluster. It consists of an 0.8 $\mathcal{M}_\odot$ DA2 white dwarf and an 0.7 $\mathcal{M}_\odot$ K2V red dwarf in a 12.5 h eclipsing orbit. It shows the "migrating wave" form of light curve characteristic of spotted stars, peculiar period changes (for a review of optical properties see Skillman & Patterson 1988), x-ray emission from both stars (with that from the white dwarf being modulated with a 9 min period) as well as x-ray absorption features attributed to material orbiting at the Lagrangian points of the system (Jensen *et al.* 1986), and ultraviolet absorption features which have been attributed to episodic mass-loss events from the red dwarf which result in a stellar wind 10^3 times as strong as the Sun's (Mullan *et al.* 1989).

There have been several previous radio observations of V471 Tau reported in the literature. Crain *et al.* (1986) report a flare of 1 mJy at 5 GHz, but no quiescent emission with an upper limit of 0.5 mJy. Morris & Mutel (1988) failed to detect V471 Tau at 5 GHz with an upper limit of 0.4 mJy. The most extensive radio observation reported so far is by Caillault *et al.* (1989), who obtained two 8 h observations (each most of a rotation) of V471 Tau at 5 GHz, four days apart. On the first day, V471 Tau was present at a flux of over 1 mJy throughout the 8 h, but showed considerable variability on time scales as short as 20 min. The peak flux was 6 mJy. There was a broad dip in the radio flux during the eclipse of the white dwarf. On the second day the flux was again above 1 mJy throughout the observation, but there was less variability than on the first day and the phase coverage did not include the eclipse. No polarization was detected.

Since white dwarfs themselves are not known to be radio sources, and since confirmation that there is radio emission associated with the white dwarf in V471 Tau has not yet been obtained, here we assume that the radio emission we detect is due to the red dwarf. A number of other rapidly-rotating K dwarfs are known to be radio sources, including AB Doradus (Lim *et al.* 1992, period 12.4 h, distance 25 pc), HD 82558 (Drake *et al.* 1990, period 1.6 days, distance 13 pc), HD 218738 (Caillault *et al.* 1988, period 3.0 days, distance 19 pc) and PZ Telescopium (Lim 1992; period 0.94 days, distance 68 pc), and thus it is not surprising that the rapidly-rotating K dwarf in V471 Tau should be a radio source. The observed radio flux implies a brightness temperature of over 10^{10} K for a stellar-sized radio source, so the emission must be nonthermal. We looked for time variability in the observations, and can rule out a single large short-lived radio flare as the cause of all the radio emission, but the radio source is not strong enough to say much about variability. The results of Caillault *et al.* (1989) suggest that there may be a component of the radio emission associated with the white dwarf, and further observations are required in order to say whether the radio emission of the K dwarf has similar characteristics to those of the other known rapidly-rotating K dwarf radio sources. There does seem to be an interesting difference between the radio emission of K dwarfs and that of M dwarf flare stars: in the latter, the 1.5 GHz emission is dominated by highly-circularly-polarized flares due a coherent emission mechanism (e.g., White *et al.* 1989). In V471 Tau, as in the other K dwarfs cited above, that does not seem to be the case.

4.2. HD 27130

HD 27130 (vB 22) has received considerable attention because it is a nearby eclipsing spectroscopic binary composed of a solar-like G6V star and a K6V star, and therefore can be used to test solar models. Outwardly, HD 27130 resembles an RS CVn system: it is composed of a G and a K star in orbits with a 5.6 day period (McClure 1982; Griffin *et al.* 1985), is a strong flaring x-ray source (Stern *et al.* 1981; Stern *et al.* 1983), and shows Ca H and K line emission indicating chromospheric activity (Wilson 1963). It is listed (along with V471 Tau) in the catalogue of chromospherically active binary stars (Strassmeier *et al.* 1988). The $v \sin i$ measurement of the G star implies that it rotates synchronously with the orbital 5.6 day period (Griffin *et al.* 1985). The distance to HD 27130 is well determined (45 pc) and is clearly consistent with membership of the Hyades cluster.

However, HD 27130 is not catalogued as an RS CVn system because it does not contain an evolved star. According to the current picture of the evolutionary status of RS CVn's (Popper & Ulrich 1977; Morgan & Eggleton 1979), they consist of binaries of two solar-mass stars which have evolved as single stars to the point where the more massive component is at the base of the giant branch and the less massive component is just leaving the main sequence; this implies an age of several billion years, i.e., much older than the Hyades group. Popper & Ulrich (1986) argue that the primary of HD 27130 is just starting to burn hydrogen in its core, in which case solar models predict that its luminosity should be about 70% of the solar luminosity; they show that the observations are consistent with this picture.

The age of HD 27130 derived by Popper & Ulrich (1986) on the basis of stellar evolution calculations is $4 \pm 2 \times 10^8$ yr, which is consistent with the age of the Hyades group. Hanson (1975) rejected HD 27130 as a member of the Hyades, but Micela *et al.* (1988) describe it as a probable member of the Hyades cluster and Schwan (1991) identifies it as a member based on a recent accurate proper

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motion measurement. Soderblom *et al.* (1990) show that it has an anomalously strong lithium absorption line for the age of the Hyades, implying that it is a younger system than most Hyads, but they note that the depletion of lithium in close binaries is still not well understood: for example, evolved RS CVn binaries are now known to have anomalously strong lithium absorption (Pallavicini *et al.* 1992).

We are unable to determine which of the two components of the binary is responsible for the radio emission. In RS CVn systems it is believed that the cool subgiant component is associated with a compact flaring component, whereas there is an extended quiescent component which encompasses both stars. In HD 27130 it is likely that the K6V secondary is the more active star. We may estimate the brightness temperature associated with the radio emission by assuming that the area of the radio source is approximately the projected area of the stellar disk of the primary. A radio flux of 0.5 mJy at 1.5 GHz requires a brightness temperature of $10^{10}\ (R/R_{\odot})^{-2}$ K, where R is the radius of the source. Unless the source is extremely large, the brightness temperature implies that here, as on RS CVn's, the emission mechanism must be nonthermal gyrosynchrotron emission, and further implies the presence of a magnetized corona.

No previous radio detection of HD 27130 has been reported: it was observed during a 1.5 GHz survey of the Taurus–Aurigae star-forming region by O'Neal *et al.* (1990) but not detected with a 3σ upper limit of 0.7 mJy, and presumably observed but not detected by Crain *et al.* (1986) in their survey of 320 Hyads at 5 GHz, with an upper limit of 0.5 mJy. We assume that it probably has radio characteristics similar to those of RS CVn systems, and is therefore likely to be a highly variable radio source.

5. THE UNDETECTED STARS

Our detection level of 0.3 mJy corresponds to a 1.5 GHz radio luminosity of 7×10^{14} ergs s^{-1} Hz^{-1} at the distance of the Hyades. Crain *et al.* (1986) reached a detection level of 1.2×10^{15} ergs s^{-1} Hz^{-1} in their 5 GHz survey, while Caillault (1989) reached 3×10^{14} erg s^{-1} Hz^{-1} at 5 GHz for a small number of x-ray bright Hyades M dwarfs. Bastian *et al.* (1988) reached a luminosity level of 6×10^{15} ergs s^{-1} Hz^{-1} in their 1.5 GHz survey of the Pleiades. By comparison, WTT stars of spectral types G–M in star-forming regions may have luminosities in excess of 10^{18} ergs s^{-1} Hz^{-1} (Feigelson & Montmerle 1985); RS CVn systems (in which the radio emission is usually coming from a G, K, or M star) have 5 GHz luminosities which can exceed 10^{17} ergs s^{-1} Hz^{-1} (Drake *et al.* 1989); and the K dwarf AB Doradus typically has a luminosity of 3×10^{15} ergs s^{-1} Hz^{-1} (flux of 5 mJy) but can exceed that by an order of magnitude (Lim *et al.* 1992). The prototypical flare star UV Ceti has a quiescent 5 GHz luminosity of only 1.7×10^{13} ergs s^{-1} Hz^{-1}, but a flare luminosity 1–2 orders of magnitude larger; however, the young southern M dwarf Rst 137B has a quiescent luminosity of 1.5×10^{15} ergs s^{-1} Hz^{-1} (Lim *et al.* 1992). Thus all these stars, with the exception of UV Ceti, would be easily detectable at the distance of the Hyades.

None of the four Hyades KO III giants were detected as radio sources. They are all known to be active stars with chromospheric and coronal emission. However, they all appear so similar in mass, age, radius, and rotation that the observed range in their activity is difficult to explain: θ^1 Tau and γ Tau are far more active than δ Tau and ϵ Tau (Baliunas *et al.* 1983). The upper limit to the brightness temperature at 1.5 GHz from the radio observations of these stars is about 10^8 K, assuming a stellar radius of about $10R_{\odot}$.

There are only a few known flare stars in the Hyades, and those we observed (vA 288, vA 351, LP 358−250 and the BY Draconis variable J331) were not detected. Stauffer *et al.* (1991) have studied the Hα emission of the low-mass stars in the Hyades and have shown that there is a clear break in the Hα properties at around $R-I=0.60$, with Hα starting to appear in emission coincident with the appearance of rapid rotation. All stars with $R-I>1.2$ (corresponding to spectral types dM2 and later) seem to have Hα in emission. They attribute their results to the dependence of activity-induced spin-down on mass: at the age of the Hyades, all stars earlier than about dM0 have already spun down and are no longer active. The nearby population of active M dwarfs is assumed to have an age similar to that of the Hyades, but seems to have even smaller values of $v \sin i$ than the Hyades population (Marcy & Chen 1992). It follows from the rotation-activity paradigm that there ought to be late-type M dwarfs in the Hyades which are still at least as active as, if not more active than, the nearby flare stars.

The stronger 1.5 GHz emissions of nearby M dwarf flare stars would be detectable at the distance of the Hyades in this survey: e.g., the 80 mJy flare on AD Leo reported by White *et al.* (1986) and the 25 mJy flare of AU Mic from Kundu *et al.* (1987) would be 1 mJy flares at the distance of the Hyades; the 35 mJy flare of YZ CMi reported by Lang & Willson (1986) would be 0.6 mJy. It is notable that each of these flares lasted for periods of time of the order of our total integration time on each field, which was 40 min. The frequency of flares at this level on nearby flare stars is not well-established: they seem to occur on active stars roughly once per 24 h, but we emphasize that this is only a guess at an unknown parameter. In a survey of 30 of the less-active nearby flare stars by White *et al.* (1989), with about 12 h of integration time at 1.5 GHz, the largest flare detected would have been 0.2 mJy at the distance of the Hyades, i.e., just below our detection level. Since these 1.5 GHz flares tend to be 100% circularly polarized, they would be more easily detected in the Stokes V maps, where there are fewer other sources, than in total intensity maps.

Bastian *et al.* (1988) compared the activity of the Pleiades flare stars with the nearby population and argued that the Pleiades flare stars could not be more than "ten times more vigorous" at radio wavelengths than the nearby population, and we wish to make a similar comparison here. We note that the statement above means that the

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flares produced by the Pleiades flare stars cannot be ten times larger than the largest flares on nearby flare stars, not that the flares can be up to ten times more frequent. As a measure of flare strength Bastian *et al.* (1988) used the product $S\tau$, where S (mJy) is the average flux density of the flare and τ (minutes) is the duration of flaring: their survey was sensitive to flares satisfying $S\tau > 27$, and their results imply that on a single Pleiades flare star such flares occur less than once per 120 h. Since this is a distance-dependent measure and we wish to compare stars at different distances, we will use instead the equivalent but distance-independent parameter $L_{15}\tau$, where L_{15} is the mean luminosity in units of 10^{15} ergs s^{-1} Hz^{-1}. The condition $S\tau > 27$ in the Pleiades corresponds to $L_{15}\tau > 500$. However, since there have in fact been no flares on nearby flare stars which would satisfy $L_{15}\tau > 500$ reported in any VLA observations, or in any other observations above 1 GHz (the three large flares on nearby dwarf stars referred to above have $L_{15}\tau \sim 50$, 90, and 70, respectively, and the largest flare detected in White *et al.*'s 1989 survey would have $L_{15}\tau \sim 13$), we do not know the frequency of such large flares on neighborhood flare stars: taking into account the number of 1.5 GHz VLA observations of nearby flare stars, it is clear that it is also well below 1 per 120 h. In the absence of any knowledge of the distribution of flare frequency as a function of $L_{15}\tau$, we are left with a lower limit to the frequency of flares with $L_{15}\tau > 500$ in the Pleiades and a lower limit to the frequency of flares at the same level in nearby stars, which cannot be compared.

In the case of the Hyades, we do at least have some idea of the rate on nearby flare stars of flares at the level detectable at the distance of the Hyades. The main problem in making a comparison is that the number of Hyades flare stars in our fields of view is poorly known. There are only five known Hyades flare stars, but this is probably just a small fraction of the total number of active dwarfs there. There are approximately 40 Hyades dMe stars in the study by Stauffer *et al.* (1991), and their Hα equivalent widths are such that most of them should be flare stars. Further, the survey of Stauffer *et al.* (1991) contains no stars redder than $R-I=1.4$, so there should be many faint M dwarf flare stars in the Hyades of type later than dM3 which are presently unidentified. As a general rule there are many more dM stars of spectral type dM3 and later than there are in the range dM0–dM2: in Petterson's (1991) list of nearby flare stars spectral types dM3 and later outnumber stars in the range dK7–dM2.5 by almost 3 to 1. We therefore adopt the assumption that there are approximately 120 flare stars in the central $4° \times 4°$ portion of the cluster, yielding a sky density of order 7 per square degree. For comparison, the known flare star population in the Pleiades, which consists mostly of K dwarfs, would produce a similar sky density if it were at the distance of the Hyades; since the known Pleiades flare stars also omit most of the (faint) M dwarf flare stars there, our assumed number still amounts to a flare star density much smaller than in the younger Pleiades.

In our observations, our detection level of 0.3 mJy and integration time of 40 min imply that we could detect any flare satisfying $S\tau > 12$ at the distance of the Hyades, or $L_{15}\tau > 30$: the three large nearby flares mentioned above all satisfy that condition. With the VLA's field of view being 0.25 square degrees, and a total observing time of about 12 h near the center of the cluster, our assumed Hyades flare star density implies that a typical Hyades flare star produces flares satisfying $L_{15}\tau > 30$ less than once every 21 h, whereas a typical nearby flare star produces flares satisfying $L_{15}\tau > 30$ roughly once every 12–24 h. This comparison depends on the unknown total number of flare stars in the Hyades and on the poorly-known frequency of large flares on nearby stars, but based on the above assumptions it seems that we could expect to have detected one or two flares in the Hyades if the late-type M dwarfs there are as active at radio wavelengths as their coeval counterparts in the solar neighborhood. In view of the uncertainties of small-number statistics, we can only argue that the Hyades M dwarfs are not much more active at radio wavelengths than the nearby population, or that if they are then their numbers are smaller than we have assumed.

One of the more interesting undetected stars in our survey is HZ 9, one of the other degenerate stars in the Hyades and therefore the remnant of one of the most massive original members of the Hyades. The reason that it is interesting is that it appears to be very similar to V471 Tau: it consists of a DA2 white dwarf in a binary orbit of period 13.5 h with a red dwarf (dM4.5e; Lanning & Pesch 1981), and is probably a post-common-envelope binary. However, it is not as active as V471 Tau. Its x-ray flux is much lower, mostly because the white dwarf in HZ 9 is much cooler (20 000 K) than that in V471 Tau (35 000 K; Guinan & Sion 1984). If, as is likely, the red dwarf is rotating synchronously, it has one of the shortest known periods of all dMe stars, and on that basis ought to be active. Rst 137B has a similar period and spectral type, and would be detected as a quiescent radio source at the distance of the Hyades. As noted above, the most active of the local population of M dwarf flare stars would be detected at the distance of HZ 9 during their stronger 1.5 GHz flares.

None of the pre-main-sequence stars in the Taurus–Auriga star-forming region serendipitously in the fields of view were detected. The radio emission of both classical T Tauri stars and weak-line T Tauri stars at 1.5 GHz is expected to be weak because their fluxes tend to fall as one goes to longer wavelengths, and most of the PMS stars were more than 10′ from a field center, so the lack of detections is not surprising.

6. THE AGE DEPENDENCE OF STELLAR RADIO EMISSION

The lack of detection of single stars in the Hyades as radio sources, when much more distant, younger single stars of the same spectral types in star forming regions are easily detected, clearly implies an age effect in radio emission. The only two stars detected as radio sources were in binaries, where orbital angular momentum can maintain rapid rotation of the component stars longer than would be true of single stars: this result is consistent with the age-rotation-activity paradigm. One of the detected stars (HD

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27130) does not have a particularly short period (5 days). V471 Tau, on the other hand, contains a K dwarf rotating as rapidly as some of the most active known K dwarfs (period of 12.5 h). These two systems provide an interesting contrast: V471 Tau is an evolved system which has spun up since the primary left the main sequence and became a red giant (prior to becoming a white dwarf), while HD 27130 is apparently still contracting towards the main sequence.

The present evidence that we have for the age dependence of stellar radio emission in single late-type dwarf stars is as follows. Many very young stars, still well above the main sequence and with a radius several times their eventual main-sequence radius, are nonthermal radio sources with very high luminosities (the weak-line T Tauri stars, which are in the age range 5×10^5–5×10^6 yr; e.g., White *et al.* 1992a). Spectral types ranging from G to M have been detected. Then there is a population of (relatively) nearby younger rapidly rotating K dwarf stars, such as AB Doradus, PZ Telescopium, and HD 82558 (ages $\sim5\times10^7$–10^8 yr), which are also found to be strong nonthermal radio sources. On the other hand, White *et al.* (1992a) found evidence that G and K dwarfs between 10^7 and 10^8 yr of age have luminosities less than 10^{15} ergs s^{-1} Hz^{-1}, and the active rapidly-rotating K dwarfs in the Pleiades (age 7×10^7 yr) have luminosities less than 4×10^{15} ergs s^{-1} Hz^{-1} (Bastian *et al.* 1988). Bookbinder (1988) reports that radio emission amongst (presumably nearby) K dwarfs is rare. The nearby single M dwarf flare stars are a prolific class of radio sources which mostly seem to be somewhat older than 10^8 yr. There is some uncertainty about their ages and whether they can be regarded as having a common origin: on kinematic criteria, the local K and M dwarfs appear to be divided roughly equally into two populations called the "young disk" and "old disk" populations, which are younger and older than $\sim5\times10^8$ yr, respectively. The young disk population is thought possibly to consist of escapees from the Pleiades cluster (e.g., Eggen 1975, 1983) and contains most of the active single flare stars. Petterson (1983) finds that some nearby active late-type dwarfs are younger than 10^8 yr based on their positions in the HR diagram, whereas Bookbinder (1985) finds the average kinematic age of the young disk stars to be 1.5×10^9 yr; Soderblom (1990) finds $\sim5\times10^8$ yr for active single stars, and concludes that they do not have a common origin. Finally, the prolific radio sources in the class of RS CVn binaries are evolved stars with ages of 2–4×10^9 yr (Popper & Ulrich 1977; Morgan & Eggleton 1979), but as noted above stars in close binaries will experience a different evolution of their rotational properties. We mention the RS CVn's because they demonstrate that rapidly-rotating stars of spectral types G to M can indeed be nonthermal radio sources despite being "old."

In general the data above are consistent with the age-rotation-activity paradigm, in the sense that radio activity of single stars seems to decrease with age, and radio activity of binary systems seems to be generally high for classes of rapid rotators whether the stars are young or old. The paradigm does not work so well at a detailed level. The main discrepancy between the observations and the paradigm is that on an individual basis stars of the same rotation rate and spectral type ought to have the same activity, but this is rarely observed to be the case in any activity indicator. This statement is equally true of radio detection: to cite a specific example, if we assume that the K6V star in HD 27130 is responsible for the radio emission, then all K6V stars with rotation periods less than 6 days and closer than 45 pc ought to be detectable as radio sources. This is not the case. As another example, the x-ray-bright G1 dwarf HD 27836 has a period of only 7 days, which is comparable to those of WTT stars. WTT stars of spectral type G are detected as steady radio sources at much larger distances than the Hyades, yet HD 27836 was not detected.

We also note that attempts to find a direct correlation between radio activity and rotation rate have so far failed, even though there appears to be a good correlation between rotation and some of the other parameters associated with stellar activity, such as x-ray emission (Pallavicini *et al.* 1981; Walter & Bowyer 1981) and Mg II flux (Hartmann *et al.* 1984; Simon & Fekel 1987). Drake *et al.* (1989) found no significant correlation between radio luminosity and rotation rate for a large sample of RS CVn stars. Caillault *et al.* (1990) and White *et al.* (1989) found a similar result for BY Draconis and M dwarf flare stars, respectively, although in those cases the statistics were poorer than for the RS CVn sample. There is an additional difficulty with this sort of study at radio wavelengths due to the problem of distinguishing between radio emission due to flares, and any steady component due to a nonthermal corona. Long studies of stars are needed to derive average flaring radio fluxes, and such long studies have generally not been possible. In any case, it is clear that radio properties do not seem to show the same direct correlation with rotation that some other activity indicators do. Thus the picture in which the dependence of stellar activity on age is produced by the rotational history of the star is not complete: there remain other parameters which must be included in order to understand why two similarly-rotating stars have different properties.

7. CONCLUSIONS

In an extensive survey of the Hyades cluster at 1.5 GHz, only 2 out of the 43 Hyads within the fields of view were detected as radio sources. The two detected stars were both spectroscopic binaries containing a rapidly-rotating K dwarf, and both were already known to be very active stars from observations at other wavelengths. The failure to detect any single stars as radio sources is generally consistent with the age-rotation-activity paradigm, according to which stellar activity is due to magnetic fields produced by dynamo action in rapidly-rotating stars and should decrease with age as a star spins down due to magnetic braking. However, the lack of detections of any M dwarf flare stars, which ought to occur in substantial numbers in the Hyades, is puzzling since the Hyades M dwarfs are of ages similar to the population of nearby flare stars and may, on

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average, be rotating more rapidly than the nearby population. The nearby population would be detectable at the distance of the Hyades during flares, and if we assume that the Hyades population has radio flare activity similar to the nearby population, then based on an estimate of the density of flare stars in the Hyades we should perhaps have detected one or two flares. Thus it appears that the Hyades M dwarf population is not more active at radio wavelengths than the nearby flare star population, or else the number of flare stars in the Hyades is much less than we assume.

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