Radio Detection of Late–Type (G–K) Dwarf Stars in the Pleiades Cluster

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ABSTRACT

We report deep 3.6 cm radio observations of a small sample of the most rapidly–rotating G–K dwarf stars in the Pleiades open cluster. Of the 4 ultra–fast rotators (UFRs) observed, 3 were detected. The G8 dwarf HII 1136, the fastest rotating G dwarf known in the Pleiades cluster, displayed a flare that rose to a peak flux density of ∼1 mJy (peak radio luminosity of $\sim 2 \times 10^{16}$ erg Hz^{-1} s^{-1}) in less than ∼1 hr, stayed at approximately this level for ∼2 hrs, and then decayed apparently exponentially with an e–folding time of ∼1.4 hrs. Following the flare, HII 1136 was detected in what may be its nonimpulsive state with a flux density of 0.16 ± 0.02 mJy. The K2 dwarf HII 1883, the fastest rotating K dwarf in the Pleiades cluster, was detected on two separate occasions. On the first occasion the star displayed two weak flares superposed on apparently steady emission with a flux density of 0.10 ± 0.02 mJy, whereas three months later the star was detected only as a steady source with a factor of ∼2 lower flux density of 0.05 ± 0.01 mJy. By contrast, the K0 dwarf HII 625 displayed slowly–varying emission with an average flux density of 0.16 ± 0.02 mJy. For all the stars detected, the average radio luminosity of their quasi–steady (perhaps quiescent) emission is 1–3 $\times 10^{15}$ erg Hz^{-1} s^{-1}. For the single undetected star, the K2 dwarf HII 3163, we placed an upper limit (5σ) of 0.12 mJy on its flux density, or 2×10^{15} erg Hz^{-1} s^{-1} on its luminosity.

Our results represent the first detection of late–type dwarf stars in the Pleiades cluster, and indeed of any apparently single stars in an open cluster. It demonstrates that solar–type stars recently descended to the zero–age main sequence can be copius radio emitters. Both in apparent quiescence and in flares, the radio luminosity of the Pleiades cluster stars is similar to that of equally rapidly rotating but relatively nearby

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late–type dwarf stars belonging to the Local Association, providing further support for the idea that such stars are physical counterparts of UFRs in the Pleiades cluster. When averaged over the stellar surface, the surface radio luminosity of the Pleiades cluster stars is comparable to that of the most active T Tauri stars, a trend recently noted for the surface soft X–ray emission of these two classes of stars. This may suggest that the magnetic dynamo of rapidly–rotating late–type stars operates at a saturated level as these stars descend to the main sequence.

Subject headings: open clusters and associations: individual (Pleiades) - radio continuum: stars - stars: flare - stars: coronae - stars: late–type - stars: evolution

1. INTRODUCTION

Open clusters constitute a natural sample of (nearly) coeval stars at the same distance and with the same chemical composition. They are important laboratories for studying stellar evolution, allowing us to disentangle (by comparison both within clusters and between clusters) the effects of different stellar properties such as mass, rotation, and chemical composition on evolution. In this endeavour one cluster that has received particular attention is the Pleiades open cluster, both for its relative proximity (distance of ∼130 pc; see discussion in Gatewood et al. 1990) and youth (age of ∼70 million yrs; see discussion in Soderblom et al. 1993a). It is second in distance only to the Hyades cluster, but is about an order of magnitude younger than the latter. At the age of the Pleiades cluster G–K dwarf stars have only recently descended to the zero–age main sequence (ZAMS), permitting us to study solar–type stars at this interesting and important stage of their evolution.

One of the surprising discoveries provided by the Pleiades cluster is that late–type (G–M) dwarf stars can arrive at the ZAMS as very rapid rotators (van Leeuwen & Alphenaar 1982). Such ultra–fast rotators (UFRs) have since been found in other young clusters such as α Persei (Stauffer et al. 1985), IC 2391 (Stauffer et al. 1989), and IC 4665 (Prosser & Giampapa 1994), as well as among a number of stars in the solar neighbourhood (see below). In the Pleiades cluster UFRs constitute about ∼20% of the population in the spectral class range G0–K7 (Soderblom et al. 1993b), whereas at lower masses, where the census is still incomplete, the fraction of UFRs is estimated to be about one–third (Stauffer & Hartmann 1987). There is no evidence that UFRs are members of binary systems, and indeed all available evidence indicates that they are single (Soderblom et al 1993b). On the basis that T Tauri stars also display a large range of rotation velocities, it is thought that only a fraction of late–type stars are born with sufficient angular momentum to become UFRs (Duncan 1993; Soderblom 1993b; see discussion in Soderblom et al. 1993c). Thus, this phase of rapid rotation is not one that all stars experience. In this view the majority of late–type stars are born as relatively slow rotators and arrive at the main sequence with projected rotation velocities

$v \sin i \leq 10$ km s^{-1}, whereas a small fraction are born as rapid rotators and eventually become UFRs with $30 \geq v \sin i \leq 150$ km s^{-1} (Soderblom et al. 1993b).

Recent deep observations of the Pleiades cluster with *ROSAT* show a clear correlation between the soft X–ray luminosity of G–M stars and their rotation velocities, with the UFRs having the strongest coronal X–ray emission (Stauffer et al. 1994). In this spectral class range stars with $v \sin i \geq 15$ km s^{-1} have similar ratios of X–ray to bolometric luminosity, $L_X/L_{bol} \approx 10^{-3}$, whereas this ratio declines rapidly for stars with slower rotation velocities. This behaviour is consistent with the idea that among convective stars rapid rotation promotes a vigorous magnetic dynamo, which saturates at the same rotational velocity for all stars; in this saturation regime the entire stellar corona is covered by X–ray emitting material with approximately the same average X–ray brightness per unit area for all stars. This study of the Pleiades cluster has considerably improved our understanding of the dependence of stellar coronal magnetic activity — as evidenced by X–ray emission — on mass and rotation velocity at a given age. Comparisons with younger clusters such as IC 2391 and α Persei, and older clusters such as the Ursa Major Group, Hyades, and Praesepe, promise to improve our understanding of the evolution of stellar coronal magnetic activity with age (see discussion in Stauffer et al. 1994).

The radio emission of stars is another important indicator of coronal magnetic activity, particularly as it provides information on nonthermal particles and magnetic field strengths in stellar coronae not otherwise obtainable. So far, however, radio surveys of the Pleiades cluster have proved singularly unsuccessful. Venugopal (1983) observed the Pleiades cluster at a wavelength of 1 m with the Ooty synthesis radiotelescope for more than 200 hrs, but did not record any emission of flux density greater than 0.75 Jy. (The significance of this upper limit was not specified; in the following, we have, for the sake of consistency, converted all quoted upper limits to 5σ). Bastian, Dulk, & Slee (1988) imaged a large area of the Pleiades cluster at 20 cm with the Very Large Array (VLA), but did not detect any emission from known member stars with flux density above 0.3 mJy; targeted observations of 5 rapidly rotating K dwarfs at 6 and 2 cm also failed to detect a single star with a flux density above 0.3–0.5 mJy. Finally, Bieging (1993) observed 27 rapidly rotating G–M dwarfs in the Pleiades cluster at 6 cm with the VLA, and did not detect a single star

In spite of the previous failures, we have been motivated to conduct a new, deeper radio survey of the Pleiades cluster for the following reason. A number of nearby, rapidly rotating, K dwarf stars — thought to be members of a supercluster called the Pleiades Moving Group or Local Association, which includes the Pleiades and α Per clusters (Eggen 1983a, 1983b) — have been found to be strong and persistent radio emitters. The best studied example is the K1–dwarf AB Doradus (HD 36705): at cm–wavelengths (here meaning 6 and 3.6 cm) this star occasionally shows rotationally–modulated flaring emission that reaches flux densities of 20–30 mJy (Lim et al. 1992; 1995a), more rarely short–duration flares that can reach even higher flux densities of over 50 mJy (Lim 1991), and most frequently persistent, quasi–steady emission with a flux density of 1–3 mJy (see Lim et al. 1995a; Lim et al. 1995b). Other Local Association K dwarfs that have been relatively well studied in radio are the K1–dwarf PZ Telescopium (HD 174429), and the

K5–dwarf "Speedy Mic" (HD 197890). At cm–wavelengths PZ Tel often displays highly variable and perhaps modulated emission with a peak flux density of up to ∼20 mJy or more, and an apparently unmodulated or quasi–steady component with a flux density of ∼1 mJy (Lim et al. 1995c); on one occasion, however, it was not detected at an upper limit of ∼0.5 mJy. So far Speedy Mic has been seen to display only slowly–varying emission with a flux density of 0.5–1.5 mJy (Robinson et al. 1994; Brown et al. 1994), but has been detected on every occasion observed. Their consistent detection over many observations — especially in the case of AB Dor — strongly suggests that these stars possess a quasi–steady radio component that seldom (if ever) drops below the abovementioned levels. The dM4e star Rositter 137B, a proper motion companion of AB Dor, is a definitive example of a quiescent emitter, always detectable as a quasi–steady source with a flux density of ∼2 mJy (Lim 1991; 1993; 1995d). The notion that (some) rapidly–rotating late–type dwarf stars of the Local Association have a well defined quiescent level is further strengthened by the recent detection of the G0 dwarf HD 129333 (Güdel et al. 1994; Güdel et al. 1995), as well as the apparent detection of the F0 dwarf HD 12230 (Güdel, Schmitt, & Benz 1995). Henceforth, we shall refer to the quasi–steady emission of these stars as their quiescent emission, keeping in mind that this level of emission represents their most typical nonimpulsive (but, perhaps as future observations may prove, not necessarily basal) emission. At distances of approximately 25, 40, and 50 pc, respectively, the radio luminosity of AB Dor, Speedy Mic, and PZ Tel during what appears to be their quiescent states is approximately 1–3×10^{15} erg Hz^{-1} s^{-1} at 3.6 cm. At the adopted distance to the Pleiades cluster of ∼130 pc, this luminosity range corresponds to a flux density range of 0.05–0.2 mJy. This range — for a flat or slowly rising spectrum between 20 cm and 3.6 cm, as is typical of the quiescent radio emission of AB Dor (Lim et al. 1994a,b) — is at or just below the detection threshold reached in the 20 cm survey of Bastian et al. (1988), and also just below the detection threshold reached in the targeted 6–cm surveys of Bastian et al. (1988) and Bieging (1993). To be able to detect stars like the abovementioned Local Association K dwarfs in quiescence at the distance of the Pleiades cluster, in our survey we have targeted a flux density threshold of 0.05 mJy, equivalent to a luminosity threshold of $\sim 1 \times 10^{15}$ erg Hz^{-1} s^{-1}.

In this paper we report the first results of our survey, based on observations of just 4 rapidly–rotating G–K dwarfs in the Pleiades cluster. Despite the small number of stars observed, and in stark contrast to previous surveys, we detected 3 of the 4 targets! In §2 we describe the observations, and in §3 the data analysis. In §4 we present the results, with particular emphasis on the association of radio sources with known stars. In §5 we discuss the implications of these results. Finally, in §6 we present our conclusions.

2. OBSERVATIONS

We conducted our survey with the VLA[2] at 3.6 cm, the most sensitive wavelength band available at this telescope. Apart from high sensitivity, observations at 3.6 cm also are less affected by confusion from background sources than at longer wavelengths, a particularly severe problem at 20 cm. In our observations we used two 50–MHz bands centered at 8.41 and 8.46 GHz. The candidate stars observed are listed in Table 1: column 1 lists the star identification number as catalogued by Hertzsprung (1947), column 2 its spectral class and column 3 its projected rotational velocity (from Stauffer & Prosser 1994), column 4 its rotation period as derived from photometric observations of starspots (from van Leeuwen, Alphenaar, & Meys 1987; Prosser et al. 1993), and in columns 5 and 6 the dates and times, respectively, of our radio observations. For comparison we also list in Table 1 the corresponding properties of AB Dor, PZ Tel, and Speedy Mic, where the radio luminosities listed refer to their quiescent emission (their flaring emission is an order of magnitude more luminous). Note that both the spectral classes and the rotation periods of the observed UFRs are similar to those of the Local Association K dwarf stars.

To achieve a flux density threshold of $\sim$0.05 mJy with the VLA operating at nominal sensitivity, we required a total integration time of 2.6 hrs on each star. In each 10 hr observing period, we were therefore able to observe 3 stars. During our first observing period in 1994 Feb 3, when the array was in D configuration, we were able to observe for just over 2 hrs because of software maintenance unrelated to our program. Although we restricted our observation to just one star, HII 1883, we did not attain our targeted detection threshold. During our second observing period in 1994 Feb 11, we observed HII 625, HII 1883 (again), and HII 3163. In this session a number of the antennas had been moved into their positions for A configuration, and long baselines involving these antennas could not be included in the analysis; this resulted in a slightly higher detection threshold than anticipated. In our rescheduled observing period in 1994 May 21, with the array in B configuration, we observed only two stars, HII 1136 and HII 1883 (again), the fastest rotating G and K dwarfs, respectively, known in the Pleiades cluster; only two stars were observed to safeguard against any unforseen loss in sensitivity. In the second and third observations we cycled through each of the target stars consecutively with an integration time of 10 mins on each star per cycle, followed by short observations of a secondary calibrator, 0336+323. We used either 3C 286 or 3C 48 as our primary calibrator.

3. DATA ANALYSIS

We edited and calibrated the data in the standard fashion using AIPS. We then made images covering the entire primary beam or larger, and searched for emission at or near the optical position of each candidate star. For all the stars observed (whether detected or undetected) we subtracted the background sources present from the visibility data, and performed a 2–dimensional

[2]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.

Fourier transform at the measured stellar radio position (or, where undetected, at the stellar optical position) as a function of time. This enabled us to study the time variability of the source (if detected), or to search for periods of enhanced emission diluted below the detection threshold in the whole–day map (if undetected). We discuss below the three criteria used to verify the stellar nature of the radio emission: (i) degree of coincidence between the radio and optical positions; (ii) time variability; and (iii) the likelihood of background source confusion.

The optical positions of the candidate stars were kindly provided to us by A. Klemola (personal communication). These positions were measured from optical plates taken at the Lick Observatory in 1973.90, converted from epoch B1950 to J2000, and corrected for proper motion by applying an average centennial proper motion for the cluster of $pm_\alpha = 1\farcs89$ and $pm_\delta = -4\farcs27$ (Jones 1973). The precision of the optical positions is estimated to be $\pm 0.5''$ or better. By comparison, the precision of our measured radio positions depends on the signal–to–noise of the detection, and also the size of the synthesized beam in the observation. We estimate the radio positional uncertainty from the relationship (Mitchell et al. 1981)

$$\Delta\alpha \ , \ \Delta\delta = (A^2(\frac{S_p}{\sigma\theta})^{-2} + B^2)^{1/2} \ \mathrm{arcsec} \ , \tag{1}$$

where $\Delta\alpha$ and $\Delta\delta$ are the uncertainties in right ascension and declination respectively, S_p/σ is the signal–to–noise ratio of the source in question, θ is the half–power beamwidth of the synthesized beam along the right ascension or declination, $A \approx 0.6$ (Wilson 1970), and B is an intensity–independent calibration error of $\sim 0\farcs1$.

We estimate the probability of background source confusion from deep imaging observations at 8.44 GHz made by Windhorst et al. (1993) with the VLA in D configuration. They report a source count of

$$N(> S_{mJy}) \approx 0.0024 \ (S_{mJy})^{-1.3} \ \mathrm{arcmin}^{-2} \ , \tag{2}$$

where $N(> S_{mJy})$ is the number of sources with flux density greater than S_{mJy}. In our observations, a variable source was detected within $\leq 0\farcs5$ of the optical position of each of three candidate stars. Even at the smallest detected source flux density of 0.05 mJy, the probability of a background source coinciding within $0\farcs5$ of the optical star position is only 0.003%; i.e., negligible. Furthermore, this level of background source confusion should be regarded as an extreme upper limit in our B configuration observations, as source overresolution in the higher spatial resolution observation decreases the source count.

4. RESULTS

The results of our survey are listed in Table 1. Column 7 lists the flux density (or 5σ upper limit) for each star, and column 8 the corresponding radio luminosity. In the following we present in greater detail the results for the individual stars.

4.1. The G8 dwarf HII 1136

HII 1136 is the most rapidly rotating G dwarf star in the Pleiades cluster. It was detected as an intensely flaring source in our single observation of this star. Figure 1 shows the temporal morphology of its emission in Stokes I (Fig 1*a*) and Stokes V (Fig. 1*b*), and Figure 2 the radio map made during the peak of the flare (integrated over 15:42–17:33 UT). As can be seen we caught the flare in its entirety, rising from the noise floor to a peak flux density of $\sim$0.9 mJy in less than 1 hr, and after remaining at this level for $\sim$2 hrs, decaying apparently exponentially with an e–folding time of $\sim$1.4 hrs. Except for the marginal detection (3.5σ) of circular polarization in the single scan centered at 18:18 UT, no circular polarization was detected throughout the entire event. Over the $\sim$2 hr duration of the flare peak (15:42–17:33 UT; Fig. 2), the upper limit placed on the degree of circular polarization of the emission is 13%. The position (in J2000 coordinates) of the radio source measured from Figure 2 (when the signal–to–noise ratio is highest), $\alpha = 03^{\rm h}\ 46^{\rm m}\ 40\overset{\rm s}{.}241\pm0\overset{\rm s}{.}007$ and $\delta = +23^\circ\ 29'\ 52\overset{''}{.}12\pm0\overset{''}{.}10$, is in excellent agreement with the optical position of HII 1136, $\alpha = 03^{\rm h}\ 46^{\rm m}\ 40\overset{\rm s}{.}229\pm0\overset{\rm s}{.}030$ and $\delta = +23^\circ\ 29'\ 52\overset{''}{.}23\pm0\overset{''}{.}50$. The nominal radio and optical positions differ by only $\sim0\overset{''}{.}2$, well within measurement uncertainties.

If the flare had continued to decay exponentially throughout its lifetime, HII 1136 would have been undetectable late in our observation. Specifically, over the period 20:24–23:53 UT the flare would have had an average flux density of only $\sim$0.05 mJy, and would have been undetectable against random noise fluctuations. Instead, during this period the star was detected at an average flux density of 0.16 ± 0.02 mJy, a factor of $\sim$3 higher than that expected from such an extrapolation. This level may represent a nonimpulsive level of emission from the star, and indeed the flux level is comparable to the average flux density at which both HII 625 and HII 1883 were detected. Over such a short time interval, however, it is difficult to distinguish low–level flaring from nonimpulsive emission.

4.2. The KO dwarf HII 625

HII 625 is among the most rapidly rotating K dwarf stars in the Pleiades cluster. It was detected as a weakly variable source in our single observation of this star. Figure 3 shows the temporal morphology of its emission in Stokes I, and Figure 4 the radio map made during its stronger period of emission from 25:16–28:44 UT. At its peak, the star reached a flux density of 0.54 ± 0.13 mJy in the scan centered at 26:29 UT. Given the high noise level of the individual scans, however, the average flux density measured over the entire observation of 0.16 ± 0.02 mJy is probably more representative of the stellar flux. No circular polarization was detected throughout the entire observation. The position of the radio source measured from Figure 4 (when the signal–to–noise ratio is highest), $\alpha = 03^{\rm h}\ 45^{\rm m}\ 21\overset{\rm s}{.}177\pm0\overset{\rm s}{.}079$ and $\delta = +23^\circ\ 43'\ 39\overset{''}{.}72\pm0\overset{''}{.}70$, is in good agreement with the optical position of HII 625, $\alpha = 03^{\rm h}\ 45^{\rm m}\ 21\overset{\rm s}{.}168\pm0\overset{\rm s}{.}030$ and $\delta = +23^\circ\ 43'\ 39\overset{''}{.}21\pm0\overset{''}{.}50$; note that the star is also detectable outside this time range of enhanced emission. The nominal radio and optical positions differ by only $\sim 0.5''$, well within measurement uncertainty. The larger apparent difference between the radio and optical positions in this case than for HII 3163 above (or HII 1883 below) is probably a result of a larger synthesized beam.

4.3. The K2 dwarf HII 1883

HII 1883 is the most rapidly rotating K dwarf in the Pleaides cluster. It was not detected in our relatively poor sensitivity observation on 1994 Feb 7, when we placed an upper limit of 0.17 mJy on its flux density. In contrast, the star was detected in the following two observations of higher sensitivity.

Figure 5 shows the temporal morphology of the radio emission from HII 1883 on 1994 Feb 11. On this day the star appeared to show two weak and short–duration flares (approximately 3σ and 5σ significance, respectively) in the scans centered at 21:43 UT and 28:16 UT, when it attained peak flux densities of 0.53 ± 0.18 mJy and 0.51 ± 0.10 mJy, respectively. We were able to verify the first flare by comparing the dirty map made in that scan with those made in adjacent scans; these maps showed a clear brightening of the star in the scan coinciding with the flare. During the second flare, however, the telescope sidelobes were badly orientated on strong confusing sources, and we were unable to unambiguously verify the reality of this flare. Averaged over the entire observation, HII 1883 had a flux density of 0.10 ± 0.02 mJy, which is not significantly changed if the two (short duration) flares are omitted. No circular polarization was detected.

Figure 6 shows the map made on 1994 Feb 21–22. On this day, the star did not show any significant time variations. Its flux density averaged over the entire observation was 0.05 ± 0.01 mJy, a factor of ~ 2 lower than in the previous observation. Again, no circular polarization was detected. The position of the radio source measured in this higher spatial resolution observation, $\alpha = 03^{\rm h}\ 48^{\rm m}\ 28\overset{\rm s}{.}020 \pm 0\overset{\rm s}{.}010$ and $\delta = +23^\circ\ 18'\ 02\overset{''}{.}97 \pm 0\overset{''}{.}11$, is in agreement with the optical position of HII 1883, $\alpha = 03^{\rm h}\ 48^{\rm m}\ 28\overset{\rm s}{.}011 \pm 0\overset{\rm s}{.}030$ and $\delta = +23^\circ\ 18'\ 02\overset{''}{.}99 \pm 0\overset{''}{.}50$, to within $\sim 0\overset{''}{.}1$. The radio and optical positions of HII 1883 measured on 1994 Feb 11 also agree to within measurement uncertainties.

4.4. The K2 dwarf HII 3163

HII 3163 has a rotation period almost identical to that of HII 625, and only a slightly later spectral class. No source was detected close enough to the optical position of this star, $\alpha = 03^{\rm h}\ 51^{\rm m}\ 53\overset{\rm s}{.}383 \pm 0\overset{\rm s}{.}030$ and $\delta = +23^\circ\ 23'\ 13\overset{''}{.}02 \pm 0\overset{''}{.}11$, to qualify as its radio counterpart. The upper limit placed on its flux density is 0.17 mJy. For the reason described in §2, on this day we did not achieve our targeted detection threshold for HII 3163, nor for the other two stars observed (and detected). If observed at the same detection threshold as HII 3163 on 1994 May 21–22, HII 1883 would not have been detected. Thus, it is possible that HII 3163 is emitting just below our detection threshold.

5. DISCUSSION

In each case the excellent agreement between the radio source position and the optical position of the candidate star, the time variability of the radio source, and the inherently low probability of a coincident background source, all make the radio detections of HII 625, HII 1136, and HII 1883 compelling. Furthermore, if all these sources had the steeply falling spectra characteristic of background sources (Windhorst et al. 1993), they very likely would have been detected (where observed; see below) at 6 cm by Bastian et al. (1988) and Bieging (1993), and at 20 cm by Bastian et al. (1988).

HII 1136 has not previously been observed in radio. As it is only one of two Pleiades cluster stars observed thus far to flare strongly in X–rays (Caillault & Helfand 1985; see Micela et al. 1990), one might wonder if it is unusually active in both X–rays and radio. We note, however, that the rapidly–rotating K2–dwarf star HII 2034 ($v \sin i \approx 75$ km s^{-1}), the other star seen to flare strongly in X–rays (Schmitt et al. 1993), was not detected in the 20–cm survey of Bastian et al. (1988), nor in the targeted 6–cm surveys of Bastian et al. (1988) or Bieging (1993). Thus, such strong flares may have a steeply rising spectrum, or more likely we just happened to catch a relatively infrequent strong flare on HII 1136. Indeed, the peak luminosity of this flare, $\sim 2 \times 10^{16}$ erg Hz^{-1} s^{-1}, is comparable to that of strong but relatively infrequent flares on both AB Dor and PZ Tel. On the latter two stars, such flares have a flat to rising spectrum between 20 and 3.6 cm (or a break at 6 cm).

HII 625 has previously been observed at 6 cm by Bieging (1993), but was not detected at an upper limit of 0.43 mJy. This is significantly above the average flux density of 0.16 ± 0.02 mJy at which we detected the star at 3.6 cm. At its peak flux density of 0.54 ± 0.13 mJy, HII 625 could (for a flat radio spectrum) have been detected by Bieging (1993) (at 6 cm); with an integration time of only about 12 mins per star, however, the likelihood of Bieging (1993) catching a short period of enhanced emission on any of the stars observed is small.

HII 1883 was observed, but not detected, by Bastian et al. (1988) and Bieging (1993) at 6 cm. Bastian et al. (1988) placed an upper limit at 6 cm for this star of 0.40 mJy, whereas Bieging (1993) placed a slightly lower upper limit of 0.30 mJy. Once again, their detection thresholds are significantly above (factor of ≥ 3) the flux density at 3.6 cm at which we detected HII 1883 on both occasions. This, and the fact that we ourselves did not detect the star in the first observation with a sensitivity a factor of ~ 2 or more poorer than the later two observations, underscores an important point. The detection threshold that we have targeted, based on the known radio properties of the Local Association K dwarf stars, must be achieved to effectively study radio emission from UFRs in the Pleiades cluster.

Our detection of late–G and early–K dwarf stars in the Pleiades cluster demonstrates unequivocally that solar–type stars recently descended to the ZAMS can be copius radio emitters. (The assertion of Güdel et al. (1995), that the radio detection of the Local Association G0 dwarf

HD 129333 demonstrates conclusively that young solar–like G stars recently descended to the ZAMS can be strong radio emitters, although persuasive, can hardly be regarded as conclusive until we truly understand the origin of the Local Association stars and their evolutionary status.) Our results represent the first, and so far only, detections of single solar–type stars in any open cluster. The only other previous detections of stars in open clusters are both binaries: the evolved precataclysmic binary system V471 Tau, and the spectroscopic late–type binary HD 27130, both of which lie in the relatively nearby Hyades cluster (see White, Jackson & Kundu 1993). V471 Tau comprises a white dwarf and a K2 dwarf in a short–period binary, which is believed to have gone through a phase of common envelope evolution; because of its uncertain evolutionary history, and possibly also poorly understood effects from its a close, condensed companion, the K2 dwarf in this system may not be representative of rapidly–rotating late–type dwarf stars in general. HD 27130 comprises a G+K dwarf binary, and resembles an RS CVn system except that it does not contain an evolved companion; this system has anomalously strong Li absorption compared to other members of the Hyades cluster. Given its binary nature and perhaps unusual properties, it may not be representative of single solar–type stars at the age of the Hyades cluster.

The radio luminosity of the detected UFRs in their slowly–variable or quasi–steady nonimpulsive states is in the range 1–3 $\times$ 10^{15} erg Hz^{-1} s^{-1}. Thus, in both their flaring and nonimpulsive states, the radio luminosity of the Pleaides cluster stars is remarkably similar to that of AB Dor, PZ Tel, and Speedy Mic. This lends new support for the idea that the latter stars — which are equally rapidly rotating, and are kinematically related to the Pleiades (and α Per) cluster — are indeed physical counterparts of UFRs in the Pleiades cluster. By contrast with our high detection rate, in a targeted 3.6 cm survey of G–K UFRs in the α Per cluster White, Prosser, & Schmitt (1993) failed to detect a single star with an upper limit in flux density of $\sim$0.1 mJy. If the Pleiades cluster was placed at the widely accepted distance to the α Per cluster of 165 pc (Crawford & Barnes 1974), then the stars we detected would appear to be 1.6 times weaker in radio; in this case, outside its strong flare HII 1136 would lie just at the detection threshold achieved in the survey of White et al. (1993), as would HII 625, and HII 1883 would not have been detected. If in fact the α Per cluster lies at a somewhat further distance, such as $\sim$190 pc as suggested by Meynet, Mermilliod, & Meader (1993) based on the most complete fit thus far to the Hertzsprung–Russel diagram for this cluster (from the same algorithm, Meynet et al. (1993) found a distance to the Pleaides cluster of $\sim$130 pc), then, apart from the strong flare on HII 1136, none of the stars we detected would have been detected by White et al. (1993).

Our high detection rate of UFRs in the Pleiades cluster permits a preliminary study of the evolution in time of the radio luminosity of late–type stars, at least at two distinct periods in time corresponding to the pre–main–sequence ($\sim$1 million yrs) and just after the ZAMS ($\sim$70 million yrs). In both their nonimpulsive and strongly flaring states, the radio luminosities of the Pleiades cluster UFRs are about an order of magnitude lower than those of the most active (weak–line) T Tauri stars in the ρ Ophiuchi and Taurus–Auriga dark clouds at 6 cm (for the radio properties of the latter stars, see André, Montmerle, & Feigelson 1987, Stine et al. 1988, O'Neal et al. 1990, Phillips, Lonsdale, & Feigelson 1991, and White, Pallavicini & Kundu 1992a,b). Many of these highly active pre–main–sequence stars are known to be rapidly rotating, and according to current thinking will probably appear as UFRs as they descend to the main sequence. Despite the large difference in their absolute radio luminosities, when normalized to the stellar surface area — T Tauri stars are typically a factor of 3 larger in radius than main sequence stars of comparable spectral class, and hence an order of magnitude larger in surface area — the surface radio luminosities of the Pleaides cluster UFRs observed and highly active pre–main–sequence stars are comparable. The same trend in coronal soft X–ray emission has been recently noted by Stauffer et al. (1994): UFRs in the Pleiades cluster have an order of magnitude lower X–ray emission than T Tauri stars of the same spectral class, but both group of stars have a similar surface X–ray luminosity. Thus, both the surface X–ray and the surface radio emission of rapidly–rotating late–type stars appear to remain constant as these stars descend to the main sequence, suggesting that their magnetic dynamos (at least as manifested in the corona) are operating in a regime of saturation. Observations of open clusters with ages intermediate between star–forming regions and the Pleiades cluster would be important for testing this idea.

6. CONCLUSIONS

We have detected, for the first time, radio emission from late–type (G–K) dwarf stars in the Pleiades cluster. Four of the most rapidly rotating late–G and early–K dwarf stars in this cluster were observed at 3.6 cm, with a sensitivity of a factor of a few better than previous surveys. On the G8 dwarf HII 1136, the fastest rotating G dwarf star in the Pleiades cluster, a strong flare was detected that reached a peak luminosity of $\sim 2 \times 10^{16}$ erg Hz^{-1} s^{-1}. Following the flare, the star was detected, possibly in its nonimpulsive state, at a luminosity similar to that of the two other Pleiades cluster stars detected. On the K2 dwarf HII 1883, the fastest rotating K dwarf star in the Pleiades cluster, two weak flares were apparently detected superposed on nonimpulsive emission. The star was redetected 3 months later as a nonimpulsive source with a factor of ~ 2 lower flux density. The K0 dwarf HII 625 was detected as a slowly varying source. Only one of the stars observed, the K2 dwarf HII 3163, was not detected. The radio luminosity of the three detected stars in their nonimpulsive states is in the range $1\text{–}3 \times 10^{15}$ erg Hz^{-1} s^{-1}.

Our results demonstrate that solar type stars that have recently descended to the ZAMS can be copius radio emitters. The radio luminosity of the observed Pleiades cluster stars in both their nonimpulsive and flaring states is similar to that of AB Dor, PZ Tel, and Speedy Mic, three equally rapidly rotating but relatively nearby K dwarf stars belonging to the Local Association. Our result therefore lends further support for the idea that such isolated (i.e., non–cluster) members of the Local Association are physical counterparts of ultra–fast rotators in the Pleiades cluster. The surface radio luminosity of the Pleiades cluster stars is comparable to that of the most active T Tauri stars in star–forming regions, a trend recently noted for the surface X–ray luminosity of these two classes of stars. This seems to suggest that the magnetic dynamo of rapidly rotating late–type stars — at least as manifested in the corona — operates at a saturated level as these stars descend to the main sequence.

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Table Legends

Table 1

Physical and radio properties of UFRs in the Pleiades cluster observed in our survey, and corresponding properties of Local Association K dwarf stars.

Figure Legends

Figure 1

Radio light curve of HII 1136 in Stokes I and V. Each point corresponds to a $\sim$10 min integration, and has an error bar of length $\pm 1\sigma$.

Figure 2

Radio map of HII 1136 in Stokes I during the peak of the flare (15:42–17:33 UT). The cross marks the optical position of the star, and has arms of length $\pm 0.5''$.

Figure 3

Radio light curve of HII 625 in Stokes I. Each point corresponds to a $\sim$10 min integration, and has an error bar of length $\pm 1\sigma$.

Figure 4

Radio map of HII 625 in Stokes I from the enhanced period of emission spanning 25:16–28:44 UT. This is the map from which the radio position of HII 625 was derived, but note that the star also is detectable outside this period. The cross marks the optical position of the star, and has arms of length $\pm 0.5''$.

Figure 5

Radio light curve of HII 1883 in Stokes I on 1994 Feb 11. Each point corresponds to a $\sim$10 min integration, and has an error bar of length $\pm 1\sigma$.

Figure 6

Radio map of HII 1883 in Stokes I on 1994 May 21–22. The cross marks the optical position of the star, and has arms of length $\pm 0.5''$.

TABLE 1.

Star number	Spectral Class	$v \sin i$ (km s^{-1})	P_{rot} (hrs)	Date	Time (UT)	$S_{3.6cm}$ (mJy)	$L_{3.6cm}$ (erg Hz^{-1} s^{-1})
HII 625	K0	94	10.3	1994 Feb 11–12	20:55–06:21	0.16 ± 0.02	3.2×10^{15}
HII 1136	G8	68	12.6	1994 May 21	14:51–23:52	0.16–0.93 ± 0.02	3.2–19×10^{15}
HII 1883	K2	140	5.6	1994 Feb 7	21:05–06:31	< 0.17	$< 3.4 \times 10^{15}$
				1994 Feb 11–12	21:05–06:31	0.10 ± 0.02	2.0×10^{15}
				1994 May 21–22	15:02–00:02	0.05 ± 0.01	1.0×10^{15}
HII 3163	K2	60	10.0	1994 Feb 11–12	21:15–06:39	< 0.12	$< 1.4 \times 10^{15}$
AB Dor	K1	100	12.4			$\sim$1–3	~ 1–3×10^{15}
PZ Tel	K1	75	22.7			$\sim$1.5	$\sim 3 \times 10^{15}$
Speedy Mic	K5	160	8.0			$\sim$0.5–1.5	~ 1–3×10^{15}