RADIO DETECTION OF LATE-TYPE (G–K) DWARF STARS IN THE PLEIADES

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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. Of the four ultrafast rotators (UFRs) observed, three were detected. The G8 dwarf H ι 1136, the fastest rotating G dwarf known in the Pleiades, displayed a flare that rose to a peak flux density of ~1 mJy (peak radio luminosity of ~2 × 10^{-6} ergs Hz^{-1} s^{-1}) in less than ~1 hr, stayed at approximately this level for ~2 hr, and then decayed apparently exponentially with an e-folding time of ~1.4 hr. Following the flare, H ι 1136 was detected in what may be its quasi steady state with a flux density of 0.16 ± 0.02 mJy. The K2 dwarf H ι 1883, the fastest rotating K dwarf in the Pleiades, was detected on two separate occasions, both times as an apparently steady source. The stellar flux density, however, appeared to change from 0.10 ± 0.02 mJy to 0.05 ± 0.01 mJy in the two observations separated by about 3 months. By contrast, the K0 dwarf H ι 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 × 10^{-7} ergs Hz^{-1} s^{-1}. For the single undetected star, the K2 dwarf H ι 3163, we placed an upper limit (5 σ) of 0.12 mJy on its flux density or 2 × 10^{-13} ergs Hz^{-1} s^{-1} on its luminosity.

Our results represent the first detection of late-type dwarf stars in the Pleiades 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 copious radio emitters. Both in their quasi-steady and flaring states, the radio luminosities of the Pleiades stars are similar to those of equally rapidly rotating but relatively nearby late-type dwarf stars belonging to the Local Association, which provides further support for the idea that such stars are physical counterparts of UFRs in the Pleiades. When averaged over the stellar surface, the surface radio luminosity of the Pleiades 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: coronae — stars: evolution — stars: flare — stars: late-type

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 because they allow 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 endeavor one cluster that has received particular attention is the Pleiades, both for its relative proximity (distance of ~130 pc; see discussion in Gatewood et al. 1990) and youth (age of ~7 × 10^6 yr; see discussion in Soderblom et al. 1993a). It is second in distance only to the Hyades but is about an order of magnitude younger than the latter. At the age of the Pleiades, G–K dwarf stars have only recently descended to the zero-age main sequence (ZAMS), which permits us to study solar-type stars at this interesting and important stage of their evolution.

One of the surprising discoveries provided by the Pleiades is that late-type (G–M) dwarf stars can arrive at the ZAMS as very rapid rotators (van Leeuwen & Alpenhaar 1982). Such ultrafast 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 neighborhood (see below). In the Pleiades UFRs constitute about ~20% of the population in the spectral class range G0–K7 (Soderblom et al. 1993b), whereas at lower masses, at which 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 predominantly members of binary systems, and indeed all available evidence indicates that the majority are single (Soderblom et al. 1993b). On the basis that T Tauri stars also display a large range of rotation velocities (see review by Bouvier 1991 and references therein; Duncan 1993), it is thought that only a fraction of late-type stars are born with sufficient angular momentum to become UFRs (Soderblom et al. 1993b; see also discussion in Soderblom et al. 1995a); 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 ≤ 10 km s^{-1}, whereas a small fraction are born as rapid rotators and eventually become UFRs with 30 ≥ v sin i ≤ 150 km s^{-1} (Soderblom et al. 1993b).

Recent deep observations of the Pleiades 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 \( \sin i \geq 15 \text{ km s}^{-1} \) 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 behavior 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 of the same spectral class. This study of the Pleiades 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 \( \alpha \) 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 accelerated populations and magnetic field strengths in stellar coronae not otherwise obtainable. So far, however, radio surveys of the Pleiades have proved singularly unsuccessful. V. R. Venugopal (1983, private communication cited in Gibson 1983) observed the Pleiades at a wavelength of 1 m with the Ooty synthesis radio telescope for more than 200 hr 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 converted all quoted upper limits to 5 \( \sigma \).) Bastian, Dulk, & Slee (1988) imaged a large area of the Pleiades 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 five 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 at 6 cm with the VLA and did not detect a single star with a flux density above 0.4–1.0 mJy (most typically 0.5 mJy). These observations reveal that the radio luminosity of near-ZAMS G–K dwarfs is significantly lower than that of the most active pre-main-sequence G–K stars in star-forming regions. The detection threshold reached, however, is effectively an order of magnitude or more higher than the luminosity range of flares seen on solar neighborhood dMe flare stars (Bastian et al. 1988). The majority of these stars are thought to be an order of magnitude older than the Pleiades but nevertheless are still descending or have recently descended to the ZAMS.

In spite of the previous failures, we have been motivated to conduct a new, deeper radio survey of the Pleiades 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 \( \alpha \) Per clusters (Eggen 1983a, b)—have been found to be strong and persistent radio emitters. The best studied example is the K1 dwarf AB Doradus (HD 36705): at centimeter 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, 1994), 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. 1994; Lim, Nelson, & Benz 1995a). Other Local Association K dwarfs that have been relatively well studied in radio are the K1 dwarf PZ Telescopium (HD 174429), and the K3 dwarf "Speedy Mic" (HD 197890). At centimeter wavelengths PZ Tel often displays highly variable and perhaps modulated emission with a peak flux density of up to \( \sim 20 \text{ mJy} \) or more and an apparently unmodulated or quasi-steady component with a flux density of \( \sim 1 \text{ mJy} \) (Lim, Nelson, & Kilkenny 1995b); on one occasion, however, it was not detected at an upper limit of \( \sim 0.5 \text{ mJy} \) (Lim et al. 1995b). 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. In addition, a number of nearby, rapidly rotating, main-sequence K dwarf stars—none of which, however, appear or have been shown to be members of the Local Association—have been detected in radio at luminosities somewhat lower than those of the above-mentioned Local Association K dwarfs (Güdel 1992, 1993); more observations are required to establish if they also are persistent radio emitters. The consistent detection of the Local Association K dwarfs 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 stated levels. The dM4e star Rositter 137B, a proper motion companion of AB Dor, is a definitive example of a quiescent emitter, always detectable at a quasi-steady source with a flux density of \( \sim 2 \text{ mJy} \) (Lim 1991, 1993, 1995). 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. 1995b), as well as the apparent detection of the F0 dwarf HD 12230 (Güdel, Schmitt, & Benz 1995a). Henceforth, we shall refer to the quasi-steady emission of these stars as their quiescent emission (keeping in mind that future observations may yet prove this not to be their 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 \( 1–3 \times 10^{15} \text{ ergs Hz}^{-1} \text{ s}^{-1} \) at 3.6 cm. At the adopted distance to the Pleiades of \( \sim 130 \) 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. 1994, 1995a)—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). In order for us to be able to detect stars such as the above-mentioned Local Association K dwarfs in quiescence at the distance of the Pleiades, in our survey we have targeted a flux density threshold of 0.05 mJy, equivalent to a luminosity threshold of \( \sim 1 \times 10^{15} \text{ ergs Hz}^{-1} \text{ s}^{-1} \).

In this paper we report the first results of our survey, which are based on observations of just four rapidly rotating G–K dwarfs in the Pleiades. In contrast to previous surveys, we detected three of the four 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\(^1\) at 3.6 cm, the most sensitive wavelength band available at this telescope. Apart

\(^{1}\) 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.
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 cataloged by Hertzprung (1947); column (2) lists its spectral class; column (3) its projected rotational velocity (from Stauffer & Prosser 1994); column (4) lists its rotation period as derived from photometric observations of starspots (from van Leeuwen, Alpenaer, & Meys 1987; Prosser et al. 1993); and columns (5) and (6) list 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; for these objects the radio luminosities listed refer to their quiescent emission (the flaring emission of AB Dor and PZ Tel 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 ~0.05 mJy with the VLA operating at nominal sensitivity, we required a total integration time of 2.6 hr on each star. In each 10 hr observing period, we were therefore able to observe three stars. During our first observing period in 1994 February 3, when the array was in D configuration, we were able to observe for just over 2 hr because of software maintenance unrelated to our program. Although we restricted our observation to just one star, H π 183, we did not attain our targeted detection threshold. During our second observing period in 1994 February 11, we observed H π 625, H π 1883 (again), and H π 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, H π 1136 and H π 1883 (again), the fastest rotating G and K dwarfs, respectively, known in the Pleiades. Only two stars were observed to safeguard against any unforeseen loss in sensitivity. In the second and third observations, we cycled through each of the target stars consecutively with an integration time of 10 minutes 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 flux 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 we 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 two-dimensional 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: (1) degree of coincidence between the radio and optical positions; (2) time variability; and (3) 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 $PM_\alpha = 1.89$ and $PM_\delta = -4.27$ (Jones 1973). The precision of the optical positions is estimated to be ±0.5 or better. By comparison, the precision of our measured radio positions depends on the signal-to-noise ratio of the detection and also on the size of the synthesized beam in the observation. We estimate the radio positional uncertainty from the relationship (Mitchell et al. 1981)

$$\Delta x, \Delta \delta = \left[ A^2 \left( \frac{2\theta}{\theta_0} \right)^2 + B^2 \right]^{1/2} \text{arcsec},$$

where $\Delta x$ and $\Delta \delta$ are the uncertainties in right ascension and declination, respectively; $S_\gamma/\theta$ is the signal-to-noise ratio of the source in question; $\theta$ 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 ~0.1.

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

$$N(>S_{\text{mb}}) \approx 0.0024(S_{\text{mb}})^{-1.3} \text{arcmin}^{-2},$$

where $N(>S_{\text{mb}})$ is the number of sources with flux density greater than $S_{\text{mb}}$. In our observations, a variable source was detected within ±0.5 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 0.5 of the optical star position is only

<table>
<thead>
<tr>
<th>Star Number</th>
<th>Spectral Class</th>
<th>$v \sin i$ (km s⁻¹)</th>
<th>$P_{\text{rot}}$ (hr)</th>
<th>Date (UT)</th>
<th>$S_{\text{VLA}}$ (mJy)</th>
<th>$L_{\gamma}$ (ergs Hz⁻¹ s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H π 625</td>
<td>K0</td>
<td>94</td>
<td>10.3</td>
<td>1994 Feb 11–12</td>
<td>20:55–06:21</td>
<td>0.16 ± 0.02</td>
</tr>
<tr>
<td>H π 1136</td>
<td>K2</td>
<td>68</td>
<td>12.6</td>
<td>1994 May 21</td>
<td>14:51–23:52</td>
<td>0.16–0.93 ± 0.02</td>
</tr>
<tr>
<td>H π 1883</td>
<td>K2</td>
<td>140</td>
<td>5.6</td>
<td>1994 Feb 7</td>
<td>21:05–06:31</td>
<td>&lt;0.17</td>
</tr>
<tr>
<td>H π 3163</td>
<td>K2</td>
<td>60</td>
<td>10.0</td>
<td>1994 Feb 11–12</td>
<td>21:15–06:39</td>
<td>&lt;0.12</td>
</tr>
<tr>
<td>AB Dor</td>
<td>K1</td>
<td>100</td>
<td>12.4</td>
<td>...</td>
<td>...</td>
<td>~1.3</td>
</tr>
<tr>
<td>PZ Tel</td>
<td>K1</td>
<td>75</td>
<td>22.7</td>
<td>...</td>
<td>...</td>
<td>~1.5</td>
</tr>
<tr>
<td>Speedy Mic</td>
<td>K3</td>
<td>160</td>
<td>8.0</td>
<td>...</td>
<td>...</td>
<td>~0.5–1.5</td>
</tr>
</tbody>
</table>
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 $5\sigma$ upper limit) for each star, and column (8) lists the corresponding radio luminosity. In the following we present in greater detail the results for the individual stars.

4.1. The G8 Dwarf H II 1136

H II 1136 is the most rapidly rotating G dwarf star in the Pleiades. 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. 1a) and Stokes V (Fig. 1b), and Figure 2 shows the radio map 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 $\sim 1.0$ mJy in less than 1 hr and, after remaining at this level for $\sim 2$ hr, decaying apparently exponentially with an $e$-folding time of $\sim 1.4$ hr. A highly impulsive event can be seen at 18:18 UT superposed on the decay phase of the strong flare; this event appears to be $\sim 100\%$ circularly polarized (3.7 $\sigma$ significance in Stokes V) and may represent a short-duration coherent burst superposed on the incoherent nonthermal emission of the main flare. Over the $\sim 2$ hr duration of the (main) 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), $\alpha = 03^h46^m40^s241 \pm 0^s007$ and $\delta = +23^\circ29'52''12 \pm 0''10$, is in excellent agreement with the optical position of H II 1136, $\alpha = 03^h46^m40^s229 \pm 0^s030$ and $\delta = +23^\circ29'52''23 \pm 0''50$. The nominal radio and optical positions differ by only $\sim 0''2$, well within measurement uncertainties.

If the flare had continued to decay exponentially throughout its lifetime, H II 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. Indeed, during this period the star was detected at an average flux density of 0.16 $\pm$ 0.02 mJy, a factor of $\sim 3$ higher than that expected from such an extrapolation. This level may represent a quasi-steady level of emission from the star, and indeed the flux level is comparable to the average flux density at which both H II 625 and H II 1883 were detected. Over such a short time interval, however, it is difficult to distinguish low-level flaring from quasi-steady emission.

4.2. The KO Dwarf H II 625

H II 625 is among the most rapidly rotating K dwarf stars in the Pleiades. 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 shows the radio map made during its stronger period of emission 25:16–28:44 UT. At its peak, the star reached a flux density of 0.41 $\pm$ 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 $\pm$ 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), $\alpha = 03^h45^m21^s177 \pm 0^s079$ and $\delta = +23^\circ43'39''72 \pm 0''70$, is in good agreement with the optical position of H II 625, $\alpha = 03^h45^m21^s168 \pm 0^s030$ and $\delta = +23^\circ43'39''21 \pm 0''50$; 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 H $\equiv$ 3163 above (or H $\equiv$ 1883 below) is probably a result of a larger synthesized beam in the radio image.

4.3. The K2 Dwarf H $\equiv$ 1883

H $\equiv$ 1883 is the most rapidly rotating K dwarf star in the Pleiades. It was not detected in our relatively poor sensitivity observation on 1994 February 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 H $\equiv$ 1883 on 1994 February 11. No significant variations were detected in its radio emission, which had an average flux density of $0.10 \pm 0.02$ mJy. Also, no significant circular polarization was detected. Figure 6 shows the map of H $\equiv$ 1883 made on 1994 May 21–22. On this day, as in the previous observation, the star did not show any significant time variations. Its flux density averaged over the entire observation, however, was only $0.05 \pm 0.01$ mJy, a factor of $\sim 2$ 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, $\alpha = 03^h48^m28.020 \pm 0.010$ and $\delta = +23^\circ 18'02.97 \pm 0.11'$, is in agreement with the optical position of H $\equiv$ 1883, $\alpha = 03^h48^m28.011 \pm 0.030$ and $\delta = +23^\circ 18'02.99 \pm 0.50$, to within $\sim 0.1$. The radio and optical positions of H $\equiv$ 1883 measured on 1994 February 11 also agree to within measurement uncertainties.

4.4. The K2 Dwarf H $\equiv$ 3163

H $\equiv$ 3163 has a rotation period almost identical to that of H $\equiv$ 625, and only a slightly later spectral class. No source was detected close enough to the optical position of this star, $\alpha = 03^h51^m53.383 \pm 0.030$ and $\delta = +23^\circ 23'13.02 \pm 0.11'$, to qualify as its radio counterpart. The upper limit placed on its flux density is 0.12 mJy. For the reason described in § 2, on this day we did not achieve our targeted detection threshold for

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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 H π 625, H π 1136, and H π 1883 compelling. Furthermore, if all these sources had the steeply falling spectra characteristic of the majority 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).

H π 1136 has not previously been observed in radio. As it is one of only two Pleiades 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 H π 2034 (ω sin i ≈ 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) or 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 H π 1136. Indeed, the peak luminosity of this flare, ~2 × 10¹⁸ ergs 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 36 cm (or a break at 6 cm).

H π 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 0.41 ± 0.13 mJy, H π 625 could (for a flat radio spectrum) perhaps have been detected by Bieging (1993) (at 6 cm); with an integration time of only about 12 minutes per star, however, the likelihood of Bieging (1993) catching a short period of enhanced emission on any of the stars observed is small.

H π 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 H π 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.

Our detection of late G and early K dwarf stars in the Pleiades confirms that solar-type stars recently descended to the ZAMS can be copious radio emitters. Our results represent the first, and 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 pre-cataclysmic binary system V471 Tau and the spectroscopic late-type binary HD 27130, both of which lie in the relatively nearby Hyades (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, 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. Given its binary nature and perhaps unusual properties, it too may not be representative of single solar-type stars at the age of the Hyades.

The radio luminosity of the detected UFRs in their slowly variable or quasi-steady states is in the range 1–3 × 10¹⁵ ergs Hz⁻¹ s⁻¹. Thus, in both their flaring and quasi-steady states, the radio luminosities of the Pleiades stars are remarkably similar to those of AB Dor, PZ Tel, and Speedy Mic. This lends new support to the idea that the latter stars—which are equally rapidly rotating and are kinematically related to the Pleiades (and z Per cluster)—are indeed physical counterparts of UFRs in the Pleiades. By contrast with our high detection rate, in a targeted 3.6 cm survey of G–K UFRs in the z Per cluster, White, Prosser, & Schmitt (1994) failed to detect a single star with an upper limit in flux density of ~0.1 mJy. If the Pleiades was placed at the widely accepted distance to the z 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 H π 1136 would lie just at the detection threshold achieved in the survey of White et al. (1994), as would H π 625, and H π 1883 would not have been detected. If in fact the z Per cluster lies at a somewhat greater distance, such as ~190 pc as suggested by Meynet, Mermilliod, & Meader (1993) based on the most complete fit thus far to the Hertzsprung-Russell diagram for this cluster (from the same algorithm, Meynet et al. 1993 found a distance to the Pleiades of ~130 pc), then, apart from the strong flare on H π 1136, none of the stars we detected would have been detected by White et al. (1994).

Our high detection rate of UFRs in the Pleiades 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 (~10⁶ yr) and just after the ZAMS (~7 × 10⁷ yr). In both their nonimpulsive and strongly flaring states, the radio luminosities of the Pleiades 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 (τ 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 Pleiades UFRs observed and highly active pre–main-sequence stars are comparable. The same trend in coronal soft X-ray emission has recently been noted by Stauffer et al. (1994): UFRs in the Pleiades have an order-of-magnitude lower X-ray
emission than T Tauri stars of the same spectral class, but both groups 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 may remain constant as these stars descend to the main sequence, which suggests 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 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. 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 H π 1136, the fastest rotating G dwarf star in the Pleiades, a strong flare was detected that reached a peak luminosity of ~2 \times 10^{16} \text{ ergs Hz}^{-1} \text{ s}^{-1}. Following the flare, the star was detected, possibly in its quasi-steady state, at a luminosity similar to that of the two other Pleiades stars detected. The K2 dwarf H π 1883, the fastest rotating K dwarf star in the Pleiades, was detected as a quasi-steady source on two separate occasions but with a factor of ~2 different flux densities. The K0 dwarf H π 625 was detected as a slowly varying source. Only one of the stars observed, the K2 dwarf H π 3163, was not detected. The radio luminosity of the three detected stars in their quasi-steady states is in the range 1-3 \times 10^{-15} \text{ ergs Hz}^{-1} \text{ s}^{-1}.

Our results confirm that solar-type stars that have recently descended to the ZAMS can be copious radio emitters. The radio luminosities of the observed Pleiades stars in both their quasi steady and flaring states are similar to those 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., noncluster) members of the Local Association are physical counterparts of ultrafast rotators in the Pleiades. The surface radio luminosity of the Pleiades 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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