Radio Observations of Rapidly Rotating F–M Dwarf Stars in the Pleiades

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ABSTRACT

We report deep 3.6 cm radio observations of six very rapidly rotating late-type dwarf stars in the Pleiades open cluster, distributed in spectral class from F9 to M0. This study, supplemented by our previous radio detections of three G8-K2 dwarfs in the Pleiades (Lim & White 1995; hereinafter LW95), completes our small census of Pleiades ultrafast rotators with spectral types spanning the range occupied by convective solar-type stars. We report the discovery of quasi-steady radio emission from the G1 dwarf H II 253, almost identical in effective temperature to the Sun, and also from the G8 dwarf H II 1136, which was previously found to be a strong flaring source by LW95. The quasi-steady radio luminosity of both these stars was $\sim 2 \times 10^{15}$ ergs Hz^{-1} s^{-1}, similar to that of the K0 and K2 dwarfs previously detected by LW95. We confirm the single nondetection reported by LW95, that of the K2 dwarf H II 3163, at a significantly lower luminosity threshold of 8.5×10^{14} ergs Hz^{-1} s^{-1}. At this luminosity threshold, none of the other stars, which have spectral types of F9, K7, and M0, were detected.

As the number of stars studied and the number of observations per star are small, we can only draw tentative conclusions at this stage. Nevertheless, our study does show that at least some solar-type stars in the Pleiades display quasi-steady radio emission at a luminosity similar to their equally rapidly rotating but relatively nearby proper motion counterparts in the Local Association. In their quasi-steady state, the most radio luminous solar-type stars in the Pleiades span the spectral class range early-G to early-K. This range also encompasses the most X-ray luminous solar-type stars in the cluster. The failure to detect stars with spectral types later than K2 is consistent with the idea that the quasi-steady radio luminosity of solar-type stars in the Pleiades, like their quiescent X-ray luminosity, decreases towards later spectral types.

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

1. INTRODUCTION

The radio emission of active late-type dwarf stars is attributed to accelerated nonthermal electron populations in strong magnetic fields. In this sense, their radio emission is similar to the nonthermal radio emission of the Sun, but is orders of magnitude stronger. Outside of flares, it is now generally recognized that at least some late-type dwarf stars display a detectable radio component that appears to be quasi steady in nature. This component, often referred to as the quiescent stellar radio emission, also involves nonthermal electrons populations (e.g., White, Lim, & Kundu 1994), but by contrast to the flaring emission remains quite steady over time scales of years. This property — a quiescent nonthermal corona — makes active late-type dwarf stars *physically* distinct from the Sun, whose quiescent radio corona is dominated by thermal electron populations (the same population seen in soft X-rays).

Until quite recently, there did not seem to be any recognizable pattern in the quiescent radio luminosity of late-type dwarf stars. For example, the first M dwarf star found always to display quiescent radio emission, the prototype dMe flare star UV Cet (Gary & Linsky 1981), has a quasi-steady radio luminosity at least an order of magnitude higher than any possessed by its binary companion L726-8A, which has almost the same spectral type (dM5e). The second M dwarf star found always to possess a quiescent radio component was the dM4e flare star Rst 137B (Lim 1993). Despite being almost the same spectral type, its quiescent radio emission is over an order of magnitude more luminous than that of UV Cet. Other dMe flare stars, however, have not been found to be such steady emitters of nonimpulsive radio emission that is observationally as strong and as stable, and hence as easily recognizeable as quiescent emission, as that seen on either UV Cet or Rst 137B (e.g., White, Jackson, & Kundu 1989). Güdel et al. (1993) presented measurements apparently consistent with quiescent emission on a large number of dMe stars, but many of the same stars were later detected at very different flux levels by White, Lim & Kundu (1994). This underlines the variability of the radio emission seen on the majority of active late-type stars. Perhaps unexpectedly, the quiescent radio luminosities of the stars studied by Güdel et al. (1993) appear to be well correlated with their quiescent soft X-ray luminosities. Both UV Cet and Rst 137B violate this correlation by being overluminous in radio. From an observational viewpoint, the suggested correlation came as a surprise because the quiescent soft X-ray luminosity of late-type dwarfs has been found to vary by less than a factor of 2 over the last decade, whereas, apart from UV Cet and Rst 137B, even outside impulsive flares the radio emission of dMe stars often varies quite erratically between observations as explained above.

By contrast with M dwarfs, rapidly rotating F to mid-K dwarfs, which have been detected in increasing numbers over the last few years although still relatively few in total (e.g., see review by White 1996), appear to show radio emission that is more often apparently steady than impulsive. Among these stars, the best observed are those belonging to the Pleiades Moving Group or, as it is more commonly known, the Local Assocation (Eggen 1975). Repeated observations of a subset of these stars demonstrate that they have, outside of flares, well defined quiescent components at similar luminosity levels (see discussion in LW95). The quiescent radio luminosity of these stars is comparable to that of the remarkable dM4e flare star Rst 137B, also a member of the Local Association, but higher than that of all other known M dwarfs (a number of which also are members of the Local Association). Güdel & Benz (1993) argue that active G and K dwarfs show the same radio/X-ray correlation shown by M dwarfs, with the exceptions of UV Cet and Rst 137B. The first F dwarf detected as a radio source, the F0 star 47 Cas (Güdel, Schmitt, & Benz 1995a), which is a member of the Local Association, has a quiescent radio luminosity comparable to that of the abovementioned G and early-K dwarfs, and follows the same radio/X-ray correlation. Subsequent F and G dwarfs detected in radio also follow the same correlation, but they include a number of older stars that cannot be members of the Local Association (Güdel, Schmitt, & Benz 1995b).

All the stars discussed above are field stars in the solar neighbourhood. Their ages, and hence stage of evolution, are difficult to accurately assess. While the rapidly rotating late-type dwarf members of the Local Assocation are generally assumed to be at the age of the α Per cluster and Pleiades (both of which also belong to the Local Association), in truth we cannot be certain since stars in this association have ages spanning the range from the Taurus Aurigae star-forming region and isolated small clouds, with ages of $\sim$2 million yrs (Eggen 1995), to the intermediate-age open cluster NGC 2287, with an age of $\sim$200 million yrs (Harris et al. 1993). Eggen (1975) has shown that early-type field stars in the Local Association can be placed on the Hertzprung-Russel diagram from near the zero-age-main-sequence (ZAMS), much younger than the somewhat evolved sequence for early-type stars displayed by the α Per cluster, to the relatively evolved sequence for early-type stars displayed by NGC 2287 (see his Fig. 3). The late-type field dwarfs belonging to the Local Association also presumably span the same age range, corresponding in evolution from the pre-main-sequence through to and well beyond the ZAMS. The ages of non-member field stars which have been detected in radio may span an even greater range. An indication that not all rapidly rotating Local Association stars of the same spectral type have similar quiescent radio luminosities, nor that they follow the abovementioned radio/X-ray correlation, is illustrated by the great disparity in the quiescent radio emission of Rst 137B and other member M dwarfs.

In this *Letter*, we report radio observations of a coeval sample of rapidly rotating late-type dwarfs with spectral types from F to M, the range occupied by convective solar-type stars. The stars studied are all established cluster members of the Pleiades, which as mentioned above is a member of the Local Association. The objective of our pilot study is to gain an understanding of the radio properties of these Pleiades solar-type stars and their radio luminosity dependence on spectral type, the first time this has been attempted for stars in an open cluster. Our (Lim & White 1995; hereinafter LW95) earlier observations of a small sample of rapidly rotating late-G to early-K dwarfs in the Pleiades established that (some) solar-type stars in this cluster are detectable radio emitters, and suggest that their radio emission outside of flares is quite steady. In addition, the apparently quasi-steady radio emission of these stars has a luminosity similar to that of rapidly rotating Local Association field stars of the same spectral types. In the present study, we extend our observations up to early-G and late-F and down to late-K and early-M dwarfs.

2. OBSERVATIONS and RESULTS

We conducted our survey with the VLA[1] at 3.6 cm, the most sensitive wavelength band available at this telescope. The observations were conducted over three 8-hr sessions on 1995 Sep 11, 23, and 25, when the VLA was in its hybrid AB configuration. This configuration was chosen because it provides the high spatial-resolution desired for a precise comparison of the radio source position with the optical star position. Two stars were observed in each session, giving a total integration time per star of just over 3 hrs. This allowed us to achieve our targeted 3σ detection threshold of 42 μJy, which at the distance to the Pleiades of $\sim$130 pc corresponds to a radio luminosity threshold of $\sim 8.5 \times 10^{14}$ ergs Hz^{-1} s^{-1}. This is sufficient to detect all the field F-K Local Association stars detected thus far in radio.

The stars selected for study are among the most rapidly rotating stars of their spectral

[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.

types, and also lie at the observed saturation boundary in coronal thermal emission as defined by the ratio of their quiescent X-ray to bolometric luminosity. They 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 (where available) 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 completeness, we also list those stars previously observed by LW95.

We edited and calibrated the data in the standard fashion using AIPS, and searched for radio emission from the candidate stars using the criteria described by LW95. The results are listed in column 7 of Table 1, where upper limits correspond to the 3σ detection threshold. Two stars were detected in the present study, the G1 dwarf H II 253 (Fig. 1) and the G8 dwarf H II 1136. H II 1136 had previously been detected by LW95, but during a strong flare which lasted nearly the entire duration of their observation. LW95 suggested that the relatively steady radio emission observed following the flare may correspond to the quasi-steady stellar radio emission, and here we confirm the detection of quasi-steady radio emission at approximately the luminosity level reported by LW95. Like LW95 we did not detect the K2 dwarf H II 3163, but at a comparatively lower luminosity threshold.

3. DISCUSSION

We have now detected 4 solar-type stars in the Pleiades, ranging in spectral types from G1 to K2. Four of the five stars observed in this spectral class range were detected on all occasions at radio luminosities exceeding $\sim 1 \times 10^{15}$ ergs Hz^{-1} s^{-1}. The single star in this group not detected in radio is the K2 dwarf H II 3163. By contrast, H II 1883, which has the same spectral type and quiescent X-ray luminosity as H II 3163, was detected by LW95 on two separate occasions at approximately the same radio luminosity (see Table 1). Except for the single highly impulsive flare observed on HII 3163 (LW95), the radio emission of all the detected stars appear to be either slowly variable or, more often, steady within the limits of detectability. Their radio luminosity at these times differ from one star to another, and between one observation and the next of the same star, only in the range 1–3×10^{15} ergs Hz^{-1} s^{-1}. Both their quasi-steady nature and similar radio luminosities suggest that these stars have been detected in their quiescent states. In addition, their quasi-steady radio emission is similar in luminosity to that of rapidly rotating early-G to early-K dwarfs that are field members of the Local Association, as was found earlier by LW95 but for a narrower range of spectral types from G8 to K2.

The G1 dwarf H II 253 is the dwarf star closest in spectral type to the Sun (G2) so far detected in radio, narrowly edging out the Local Association G0 dwarf EK Dra (Güdel et al. 1995). While important for understanding the evolution in the coronal radio emission of truly solar-like stars, we caution against using this detection to imply that the Sun necessarily possesed a radio luminosity as high as that of H II 253 when it was at the age of the Pleiades ($\sim$70 million yrs). G (and K–M) dwarfs in the Pleiades (and other young open clusters) show a bimodal distribution in their rotation periods, with $\sim$20% of stars having short rotation periods (known as ultrafast rotators) and the remainder having relatively long rotation periods. One line of thought is that some stars are born as fast rotators and become similar to the ultrafast rotators seen in the Pleiades, while the majority are born as slow rotators and never experience a phase of rapid rotation (see short review in SW95). We do not know *posteriori* whether the Sun arrived on the ZAMS as an ultrafast rotator, or whether it never experienced a phase of truly rapid rotation. If the latter, then it may never have possessed a radio (and X-ray) corona as prodigious as H II 253 following the T Tauri stage.

The F9 dwarf H II 476 is one of the most X-ray luminous, and also among the most rapidly rotating, F dwarfs in the Pleiades. It lies close to the saturation boundary in coronal thermal emission as defined by its quiescent X-ray to bolometric luminosity, which for F dwarfs has the value $L_x/L_{bol} \approx 10^{-4}$. Despite being only slightly earlier in spectral type than the G1 dwarf H II 253, it was not detected at a factor of $\sim$2 lower radio luminosity. The X-ray luminosity of H II 476, however, is nearly an order of magnitude lower than that of H II 253 (although some of this difference may be due to intrinsic variability; the quiescent X-ray luminosities of Pleiades dwarfs vary by up to a factor of 2 over time scales of years), and is comparable only to that of the K7 dwarf H II 1531, which also was not detected in radio. We note that the F0 dwarf 47 Cas, detected in radio by Güdel, Schmitt, & Benz (1995), has a quiescent X-ray luminosity nearly an order of magnitude higher than that of the F9 dwarf H II 476. There are no early-F dwarfs in the Pleiades with the X-ray luminosity of 47 Cas, a member of the Local Association, nor, for that matter, in the younger ($\sim$50 million yrs) α Per cluster (Randich et al. 1996).

The M0 dwarf H II 212 is among the most rapidly rotating and most X-ray luminous M dwarfs in the Pleiades. It makes for an interesting comparison with the field Local Association M4 dwarf Rst 137B, which has the same ratio of L_x/L_{bol} and a comparable (actually somewhat smaller) projected angular velocity. With a typical quiescent flux density of $\sim$2 mJy at 3.6 cm (Lim 1993), Rst 137B has, at its now more accurately determined distance of 15 pc (Guirado et al. 1996), a typical quiescent radio luminosity of $\sim 5 \times 10^{14}$ ergs Hz^{-1} s^{-1}. If H II 212 were to possess the same quiescent radio luminosity as Rst 137B, it would lie just below our detection threshold. On the other hand, if the quiescent radio luminosity of

Rst 137B is typical of rapidly rotating M4 dwarfs in the Pleiades, and if the quiescent radio luminosity of rapidly-rotating dwarfs in this cluster increases towards earlier spectral types (at least among M dwarfs), then one might expect H II 212 to have been detected above our luminosity threshold. Specifically, M0 dwarfs at the saturation boundary in coronal X-ray activity have a quiescent X-ray luminosity twice that of M4 dwarfs. If the same dependence were to apply to their quiescent radio luminosity, as found by Güdel et al. (1993) for M dwarfs at the saturation boundary in coronal X-ray activity, then H II 212 should have been detected at a quiescent radio luminosity of $\sim 1 \times 10^{15}$ ergs Hz^{-1} s^{-1}. Our null detection of H II 212 serves again to emphasize the remarkable quiescent radio luminosity of Rst 137B.

Given the small number of stars observed and the relatively few observations per star, together with the upper limits established for stars later than spectral type K2, we can draw only tentative conclusions at this stage regarding the dependence of the quiescent radio luminosity of solar-type stars on spectral type. Nevertheless, our observations strongly suggest that, in their quiescent state, the most radio luminous solar-type stars in the Pleiades occupy the spectral class range early-G to early-K. Furthermore, within this range the radio luminosities of the detected stars are essentially similar, with their observed intrinsic variability of a factor of ~ 2 dominating any systematic differences between these stars. The null detection of the K2 dwarf H II 3163, however, points to a larger spread in the quiescent radio luminosity of rapidly rotating stars in this spectral class range than that indicated solely by those detected. For comparison, the quiescent X-ray luminosity of solar-type stars in the Pleiades peak at early-G; indeed, the G1 dwarf H II 253 is the most luminous X-ray source in the Pleiades (Stauffer et al. 1994). In our sample of radio detected stars, the quiescent X-ray luminosity of the G1 dwarf H II 253 is a factor of ~ 6 times higher than that of the K2 dwarf H II 1883, but as mentioned above their quiescent radio luminosity is similar to within a factor of ~ 2.

Our null detection of the F9 dwarf H II 476 tentatively suggests that the quiescent radio luminosity of rapidly rotating solar-type stars in the Pleiades decreases as one goes from spectral type G to F. This would be consistent with the relatively weaker quiescent X-ray luminosity of the most X-ray luminous F dwarfs compared to the most X-ray luminous G dwarfs in the Pleiades. Our null detections of spectral types later than K2, including the null detection of one K2 dwarf, suggests that the quiescent radio luminosity of rapidly rotating solar-type stars in the Pleiades decreases as one goes from spectral type G/early-K to late-K/early-M. This again would be consistent with the observed monotonic decrease in the quiescent X-ray luminosity of rapidly-rotating dwarfs with spectral type from G to M. We note, however, that our observations do not rule out the possibility that all solar-type stars lying at the saturation boundary for coronal X-ray emission have the same ratio of quiescent radio to bolometric luminosity, implying that, relatively to the total stellar radiative output, all these stars have equally prodigious nonthermal coronae. Observations with significantly higher sensitivity are required to test this hypothesis.

4. SUMMARY and CONCLUSIONS

We have observed at 3.6 cm eight solar-type stars in the Pleiades distributed in spectral class from late-F to early-M. Four stars were detected, with spectral types G1, G8, K0, and K2; i.e., spanning the range early-G to early-K. The detected stars have quiescent radio luminosities lying in the narrow range 1–3 $\times$ 10^{15} ergs Hz^{-1} s^{-1}. At a luminosity threshold of 8.5×10^{14} ergs Hz^{-1} s^{-1}, none of the other stars (spectral types F9, K2, K7, and M0) were detected. Our central conclusion is that, in their quiescent state, the most radio luminous solar-type stars in the Pleiades lie in the spectral class range early-G to early-K, the same range occupied by the most X-ray luminous stars. We tentatively conclude that the quiescent radio luminosity of rapidly rotating solar-type stars in the Pleiades decreases towards spectral type F, as well as towards spectral type late-K/early-M. This again would be consistent with the observed dependence in the quiescent X-ray luminosity of rapidly rotating solar-type in the Pleiades with spectral type. Derivation of the actual functional dependence in the quiescent stellar radio luminosity with spectral type, however, requires observations with sensitivity not achieveable at present with the VLA in realistic observing times. Such observations will have to await a future planned upgrade of the VLA.

We thank C. Prosser for providing us with a comprehensive list of the spectral classes and rotational velocities of late–type dwarf stars in the Pleiades cluster from the LTSA Database on Open Clusters, maintained at the Center for Astrophysics by J. Stauffer and C. Prosser. We are grateful to A. Klemola for checking the optical positions of the stars observed. J. Lim acknowledges the support of an Academia Sinica Postdoctoral Fellowship. S. White acknowledges support for stellar radiophysics from NSF grant 92-17891.

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TABLE 1. Physical Parameters and Radio Luminosity of Observed Pleaides Stars

Star number	Spectral Class	$v \sin i$ (km s^{-1})	$P_{\rm rot}$ (hrs)	Date	Time (UT)	$S_{3.6\ \rm cm}$ (mJy)	$L_{3.6\ \rm cm}$ (ergs Hz^{-1} s^{-1})
H II 476	F9	23		1995 Sep 11	08:07–15:29	< 0.042	$< 8.5 \times 10^{14}$
H II 253	G1	37		1995 Sep 11	08:12–15:41	0.085 ± 0.014	1.7×10^{15}
H II 1136	G8	68	12.6	1994 May 21[a]	14:51–23:52	$0.16^{\rm b}$–$0.93^{\rm c} \pm 0.02$	$3.2^{\rm b}$–$19^{\rm c} \times 10^{15}$
				1995 Sep 23	07:12–14:41	0.092 ± 0.014	1.9×10^{15}
H II 625	K0	94	10.3	1994 Feb 11–12[a]	20:55–06:21	0.16 ± 0.02	3.2×10^{15}
H II 1883	K2	140	5.6	1994 Feb 7[a]	21:05–06:31	< 0.17	$< 3.4 \times 10^{15}$
				1994 Feb 11–12[a]	21:05–06:31	0.10 ± 0.02	2.0×10^{15}
				1994 May 21–22[a]	15:02–00:02	0.05 ± 0.01	1.0×10^{15}
H II 3163	K2	60	10.0	1994 Feb 11–12[a]	21:15–06:39	< 0.12	$< 2.4 \times 10^{15}$
				1995 Sep 23	07:12–14:41	< 0.042	$< 8.5 \times 10^{14}$
H II 1531	K7	50	11.5	1995 Sep 25	07:04–14:34	< 0.042	$< 8.5 \times 10^{14}$
H II 212	M0	75		1995 Sep 25	07:18–14:47	< 0.042	$< 8.5 \times 10^{14}$

(a)From LW95
(b)The luminosity of the star following the flare, in perhaps its quasi-steady state (LW95)
(c)The luminosity of the star at the peak of the flare

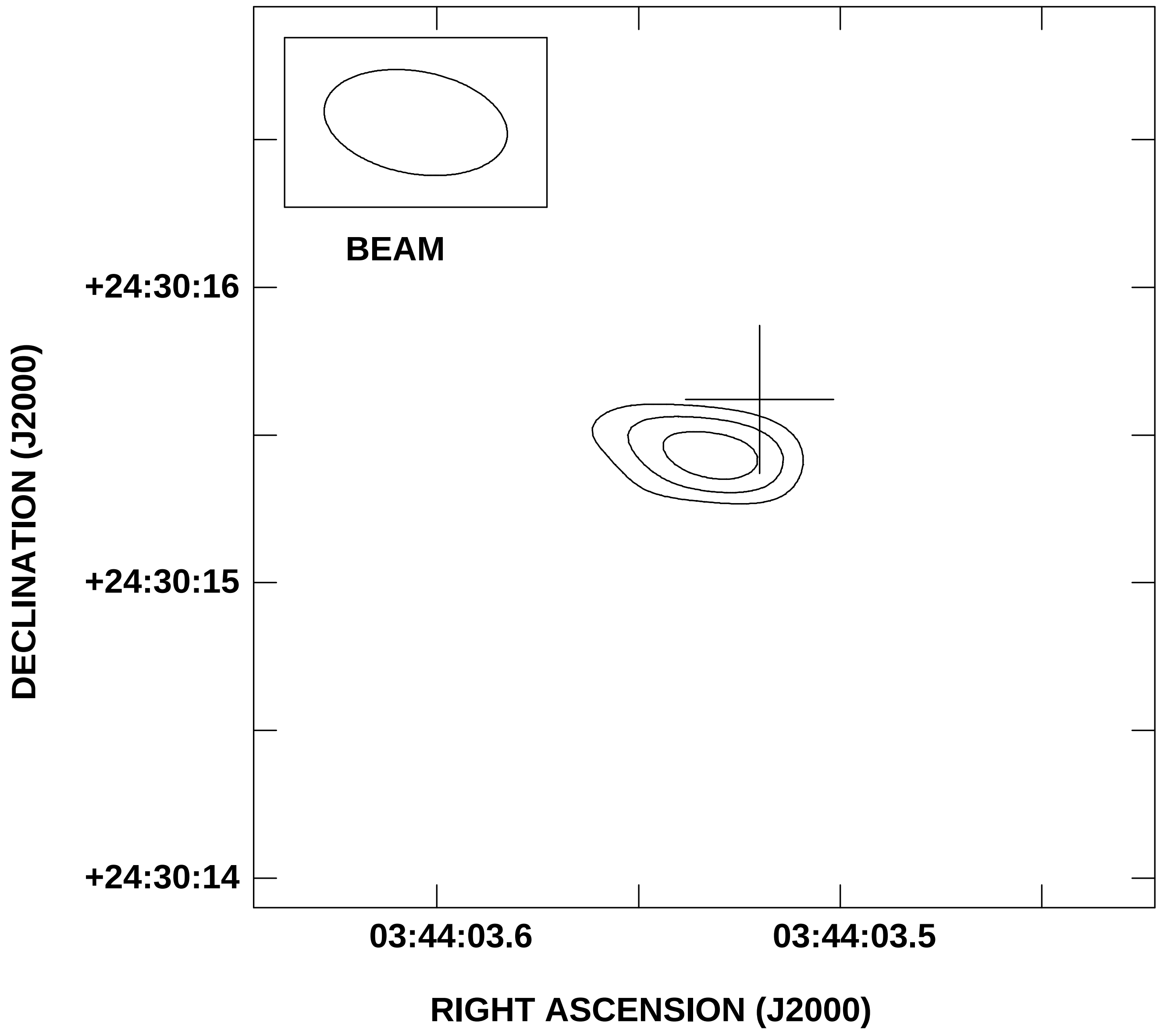

FIG. 1.—Radio map of H II 253 in Stokes I on 1995 Sep 11. The cross marks the optical position of the star, $\alpha = 03^{\rm h}\ 44^{\rm m}\ 03\overset{\rm s}{.}520 \pm 0\overset{\rm s}{.}030$ and $\delta = +24^\circ\ 30'\ 15\overset{''}{.}62 \pm 0\overset{''}{.}50$ (Klemola (1996), measurements of Lick plates precessed from B1950 to J2000 and corrected for the E term of aberration, the FK4 equinox zero–point error, and proper motion at the mean Pleiades rate), and has arms of length $\pm 0.5''$. The centroid of the radio source is at $\alpha = 03^{\rm h}\ 44^{\rm m}\ 03\overset{\rm s}{.}534 \pm 0\overset{\rm s}{.}036$ and $\delta = +24^\circ\ 30'\ 15\overset{''}{.}44 \pm 0\overset{''}{.}28$, formally compatible with the optical stellar position.