NEW RADIO DETECTIONS OF EARLY-TYPE PRE-MAIN-SEQUENCE STARS

STEPHEN L. SKINNER, ALEXANDER BROWN, AND JEFFREY L. LINSKY

Joint Institute for Laboratory Astrophysics, University of Colorado and National Institute of Standards and Technology

Received 1990 January 16; accepted 1990 April 23

ABSTRACT

We present results of VLA radio continuum observations of 13 early-type pre-main-sequence stars selected from the 1984 catalog of Finkenzeller and Mundt. The stars HD 259431 and MWC 1080 were detected at 3.6 cm, while HD 200775 and TY CrA were detected at both 3.6 and 6 cm. The flux density $S_v$ of HD 200775 has a frequency dependence of the form $S_v \propto v^{-0.50±0.03}$, consistent with the behavior expected for free-free emission originating in a fully ionized wind. However, an observation in A configuration suggests that the source geometry may not be spherically symmetric. In contrast, the spectral index of TY CrA is negative with a flux behavior of the form $S_v \propto v^{-0.15±0.1}$, implying nonthermal emission. The physical mechanism responsible for the nonthermal emission has not yet been identified, although gyrosynchrotron and synchrotron processes cannot be ruled out.

Subject headings: stars: massive — stars: pre-main-sequence — stars: radio radiation — stars: winds

I. INTRODUCTION

Herbig Ae/Be stars (Herbig 1960) are believed to be massive ($\geq 2 M_\odot$) young stars still gravitationally contracting toward the main sequence (Strom et al. 1972). These objects typically show emission lines in their spectra, lie in obscured regions, and illuminate nearby nebulosity. Herbig (1960) identified 26 objects of this type, and this list was later extended by Finkenzeller and Mundt (1984) to a total of 57 pre-main-sequence (PMS) stars with spectral types in the range O7-F0.

Radio continuum observations of these young stars can provide valuable information on mass-loss rates due to ionized winds (Wilking, Mundy, and Schwartz 1986) and also offer the exciting prospect of revealing nonthermal behavior (Güdel et al. 1989). Although nonthermal radio emission is typically associated with the presence of magnetic fields (cf. Dulk 1985), it is not clear how such fields would be maintained in early-type PMS stars, which are not expected to have prominent outer convection zones (Iben 1965; Mestel 1978).

Our present understanding of radio continuum emission in early-type PMS stars is incomplete. The ubiquity of this emission is not well-determined since roughly half of the known stars in this class have never been observed at radio wavelengths. Radio data are sparse for those few objects which have been detected, and the origin of the emission is typically not known. An exception is the Herbig Be star LkHα 234, whose emission is believed to originate in a partially ionized wind via the free-free mechanism (Wilking, Mundy, and Schwartz 1986).

We have initiated a program aimed at determining which of the 57 massive PMS stars cataloged by Finkenzeller and Mundt (1984) are radio sources and identifying plausible emission mechanisms. Here, we report on the initial phase of this program in which 13 such stars were observed using the NRAO Very Large Array (VLA). The stars HD 259431 and MWC 1080 were detected at 3.6 cm, while HD 200775 and TY CrA were detected at both 3.6 and 6 cm. These observations lend considerable support to the presence of an ionized wind in HD 200775, as previously suspected on the basis of IUE observations (Grady, Imhoff, and Bjorkman 1988). In addition, TY CrA is found to be a nonthermal radio source, providing indirect evidence that magnetic fields may be present in some early-type PMS stars.

II. OBSERVATIONS

Program stars and observing dates are given in Tables 1 and 2. For these observations, we selected stars from Finkenzeller and Mundt (1984) for which few or no previous radio data existed. The only exception was TY CrA, which was previously detected at 6 cm by Brown (1987) and was observed here in order to determine its spectral index. Some priority was given to observing stars which were suspected to have winds or outflows.

The VLA was in A configuration on 1989 February 2 and A/B configuration on February 15 and March 7–8. Our primary observing wavelength was 3.6 cm, which provides maximum VLA sensitivity and eliminates most bright extragalactic background sources. Multiwavelength observations were obtained for TY CrA (3.6/6 cm) and HD 200775 (3.6/6/20 cm). Typical integration times at 3.6 cm were 40–60 minutes per star, yielding rms noise levels of $\sim 30 \mu$Jy (1σ) and detection thresholds of $\sim 90 \mu$Jy (3σ).

Our observations and data reduction followed standard VLA procedures. A bandwidth of 50 MHz was utilized in each of two orthogonal polarization channels, which were centered at the effective observing frequencies 1.49, 4.86, and 8.44 GHz. Standard VLA phase calibrators were observed at time intervals of 20–25 minutes. Absolute flux calibration was achieved by observing 3C 48 on 1989 February 2 and 15 and 3C 286 on 1989 March 7 and 8. Cleaned maps were produced using the

$S_v$ is the radio flux density at frequency $v$. The spectral index is the exponent $a$ in the power-law fit $S_v \propto v^a$, where $S_v$ is the radio flux density at frequency $v$. 

1 Department of Physics, University of Colorado.
2 Staff Member, Quantum Physics Division, National Institute of Standards and Technology.
3 The National Radio Astronomy Observatory (NRAO) is operated by Associated Universities, Inc. under cooperative agreement with the National Science Foundation.
AIPS\textsuperscript{5} task MX, utilizing natural weighting to maximize sensitivity. Cleaned 3.6 cm maps are shown in Figures 1–4 with optical positions superimposed.

The 6 and 20 cm maps for HD 200775 contained a pair of bright compact sources 4' east of the star. The interfering sidelobes were successfully removed by performing a phase-only self-calibration (ASCAL) followed by deep cleaning with MX.

The peak and integrated fluxes for each detected star are given in Table 1. Fluxes were measured with the AIPS task IMFIT (two-dimensional Gaussian fit) and were verified with negative spectral index points to a nonthermal origin for the Table 2.

III. COMMENTS ON INDIVIDUAL SOURCES

a) TY Coronae Australis

This is clearly an unusual star. It does not show H\alpha emission rising above the continuum as do most other early-type PMS stars in Finkenzeller and Mundt (1984), but its location within the CrA dark cloud and its association with bright reflection nebulosity strongly suggest that it is a very young object (see Cardelli and Wallerstein 1989; Wilking, Taylor, and Storey 1986). It has been reported to be an eclipsing variable (Kar'dopolov, Sahanimok, and Filip'ev 1981) and is the only star in our program that is known to be an X-ray source (Walter and Kuhi 1981).

We detected TY CrA at both 3.6 and 6 cm, and the source was unresolved at both wavelengths. No circular polarization was detected, with an upper limit on fractional circular polarization of \( \pi_c \leq 0.1 \) (3 \( \sigma \)). Our peak 6 cm flux of 1.58 mJy is slightly larger than the peak value of 1.24 mJy measured previously by Brown (1987). The integrated fluxes in Table 1 imply a two-point spectral index of \( \alpha_{6,6} = -0.15 \pm 0.1 \) (1 \( \sigma \)), and this negative spectral index points to a nonthermal origin for the radio emission. Here, and in the following, we have estimated the error on the spectral index by adding/subtracting the 1 \( \sigma \) rms noise to/from the 3.6/6 cm integrated fluxes (and vice versa).

A useful discriminant between thermal and nonthermal radio emission is the brightness temperature \( T_b \). However, \( T_b \) cannot accurately be determined unless the source size \( R_s \) is known. Assuming a distance to TY CrA of 130 pc (Marraco and Rydgren 1981), a stellar radius \( R_s \approx 2.7 \) \( \Omega_\odot \) consistent with spectral type B9, and using the 3.6 cm integrated flux from Table 1, we obtain (see Gary 1985)

\[
R_s^2T_b \approx 10^6 \ K.
\]

In the above, \( R_s \) is expressed in units of stellar radii. If the size of the radio source region is comparable to that of the star, then \( R_s \approx 1 \) and the above result gives \( T_b \approx 10^6 \) K. A brightness temperature of this magnitude would rule out optically thin free-free emission (which can also produce a negative spectral index) but would be consistent with gyrosynchrotron and synchrotron emission (Dulk 1985, 1987).

b) HD 200775

Well-developed P Cygni profiles in Mg \( \alpha \) (Grady, Imhoff, and Bjorkman 1988) provide evidence that this star has a strong wind, and the CO observations of Watt et al. (1986) suggest that HD 200775 is driving a bipolar outflow with lobes aligned approximately in a NE-SW direction.

TABLE 1

<table>
<thead>
<tr>
<th>DATE (1989)</th>
<th>STAR</th>
<th>SPECTRAL TYPE ( c )</th>
<th>DISTANCE (pc)</th>
<th>FLUX (mJy)</th>
<th>PEAK FLUX (mJy)</th>
<th>S/N ( b )</th>
<th>VLA PEAK POSITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar 7</td>
<td>B3e + s</td>
<td>600</td>
<td>3.6( \pm 0.3 )</td>
<td>0.20</td>
<td>7</td>
<td>2 ( \odot )</td>
<td>59.66 + 67.55</td>
</tr>
<tr>
<td>Mar 7</td>
<td>B3e + s</td>
<td>600</td>
<td>3.6( \pm 0.3 )</td>
<td>0.52</td>
<td>18</td>
<td>2 ( \odot )</td>
<td>59.74 + 67.55</td>
</tr>
<tr>
<td>Mar 7</td>
<td>B3e + s</td>
<td>600</td>
<td>3.6( \pm 0.3 )</td>
<td>0.36</td>
<td>7</td>
<td>2 ( \odot )</td>
<td>59.70 + 67.55</td>
</tr>
</tbody>
</table>

TABLE 2

<table>
<thead>
<tr>
<th>DATE (1989)</th>
<th>STAR</th>
<th>SPECTRAL TYPE ( c )</th>
<th>DISTANCE (pc)</th>
<th>FLUX (mJy)</th>
<th>3 ( \sigma ) UPPER LIMIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb 2</td>
<td>VV Ser</td>
<td>A2( b )</td>
<td>245( b )</td>
<td>3.6( \pm 0.3 )</td>
<td>0.09</td>
</tr>
<tr>
<td>Feb 15</td>
<td>HK Ori</td>
<td>A4e</td>
<td>460</td>
<td>3.6( \pm 0.3 )</td>
<td>0.11</td>
</tr>
<tr>
<td>BD + 9( \circ )880</td>
<td>A5e</td>
<td>Uncertain</td>
<td>460</td>
<td>3.6( \pm 0.3 )</td>
<td>0.09</td>
</tr>
</tbody>
</table>

5 Astronomical Image Processing System (AIPS) is a data reduction software package developed by NRAO.

\[ \text{S/N} = \frac{\text{peak flux}}{\text{rms noise}} \]

\[ \text{S/N} \text{ upper limit} = \frac{\text{peak flux}}{\text{rms noise}} \]

\[ \text{S/N} = \frac{\text{peak flux}}{\text{rms noise}} \]

© American Astronomical Society • Provided by the NASA Astrophysics Data System
Fig. 1.—Cleaned 3.6 cm VLA map of TY CrA observed on 1989 March 7 in A/B configuration. Outer contour is 0.18 mJy (5σ), and interval between contours is 0.18 mJy (= 5σ increments). Irregular beam shape is due to southerly declination of TY CrA. Cross denotes SAO optical position corrected for proper motion, with uncertainty of 0′′.21 (1σ).

Fig. 2.—Cleaned 3.6 cm VLA map of HD 200775 observed on 1989 March 7 in A/B configuration. Outer contour is 87 μJy (3σ), and contour interval is 58 μJy (= 2σ increments). Cross denotes SAO optical position corrected for proper motion, with uncertainty of 0′′.32 (1σ).

Fig. 3.—Cleaned 3.6 cm VLA map of HD 259431 observed on 1989 February 15 in A/B configuration. Outer contour is 66 μJy (3σ), and contour interval is 11 μJy (= 0.5σ increments). Cross denotes optical position from the Lick astrometric program (Herbig and Bell 1988), corrected for proper motion. Positional uncertainty is not known.

Fig. 4.—Cleaned 3.6 cm VLA map of MWC 1080 observed on 1989 March 8 in A/B configuration. Outer contour is 66 μJy (3σ), and contour interval is 22 μJy (= 1σ increments). Optical position (A) is from Altenhoff et al. (1976) with no correction for proper motion, which has an uncertainty ≥ 1″. Optical position (B) is from Curiel et al. (1989) and is based on a CCD image (I filter). Positional uncertainty is not known. The CO peak identified by Cantó et al. (1984) is nearly coincident with optical position (B).
Our initial observation of HD 200775 at 3.6 cm in A configuration (HPBW = 0.33") shows an emission lobe extending in an E-NE direction out to an angular separation of 0'7 from the center of an unresolved point source. If real, this extended structure would imply nonspherical geometry for the emitting region. However, on the basis of a single A configuration observation, we cannot exclude the possibility that the extended emission is image smearing due to short-term atmospheric phase fluctuations.

Our follow-up multiwavelength observation in A/B configuration shows an unresolved source at both 3.6 cm (Fig. 2) and 6 cm, and the 3.6/6 cm integrated fluxes in Table 1 give a spectral index of $\alpha = 0.50 \pm 0.3$ (1 $\sigma$). In computing the 6 cm integrated flux, a Gaussian taper was applied at 200 k$\lambda$ to obtain a beam size comparable to that obtained at 3.6 cm. This spectral index is consistent with the value of $\alpha$ = 0.6 expected for free-free emission originating in a spherically symmetric, fully ionized wind (Panagia and Felli 1975) and is also consistent with nonspherical wind emission (Schmid-Burgk 1982; Reynolds 1986).

In the case of a spherical wind (Panagia and Felli 1975) the 3.6 cm flux of 0.58 mJy would imply a mass-loss rate of $M = 2.4 \times 10^{-7} M_\odot$ yr$^{-1}$, where we have assumed a wind velocity of 250 km s$^{-1}$ (see Grady, Imhoff, and Bjorkman 1988) and a distance of 600 pc (Finkenzeller and Mundt 1984). This is a factor of ~3 less than the value obtained using the mass-loss rate equation of Altamore et al. (1980), which is based on IUE, optical, and infrared observations of HD 200775.

Thus, the observed value of the spectral index and the mass-loss rate calculations given above lead us to believe that the observed radio emission of HD 200775 is free-free emission originating in an ionized wind, although our A configuration observation suggests that an assumption of spherical symmetry may not be appropriate.

c) HD 259431

High-dispersion IUE spectra of this star show distinctive P Cygni profiles in Mg II and suggest the presence of a strong wind (Grady, Imhoff, and Bjorkman 1988). No estimate of the radio spectral index is yet available. Assuming that we have detected free-free emission in a fully ionized, spherically symmetric wind with a wind velocity of 350 km s$^{-1}$, then the 3.6 cm integrated flux of 0.13 mJy would imply a mass-loss rate of $M \approx 1.7 \times 10^{-7} M_\odot$ yr$^{-1}$.

d) MWC 1080

This star shows a P Cygni profile at H$\alpha$ (Garrison and Anderson 1977) and is associated with a powerful molecular outflow (Cantó et al. 1984; Levreault 1988). Several previous attempts to detect continuum radio emission in MWC 1080 have yielded negative results (Altenhoff et al. 1976; Rodriguez and Cantó 1983; Evans et al. 1987). The 6 cm sources discussed by Curiel et al. (1989) are more than 10" from the optical position.

Due to the presence of extended nebulosity, the optical position of MWC 1080 is not well determined, and proper motion data are not available. In Figure 4 we show the optical position of Altenhoff et al. (1976), which has an uncertainty $\geq 1^\prime$, and also the optical position given by Curiel et al. (1989), which is based on a CCD (I filter) image. The latter position lies $\sim 1.5^\prime$ north of our 3.6 cm continuum peak, which we consider to be reasonably good agreement given the difficulties associated with determining the optical position.

If we are observing free-free radio emission originating in a spherically symmetric wind, the inferred mass-loss rate would be $M = 1.7 \times 10^{-6} M_\odot$ yr$^{-1}$, where we have assumed a wind velocity of 500 km s$^{-1}$ and a distance of 2200 pc (Levreault 1988). This mass-loss rate is a factor of ~2 less than the value of $M = 3.1 \times 10^{-6} M_\odot$ yr$^{-1}$ obtained by Levreault (1988) on the basis of molecular outflow measurements.

e) Undetected Stars

The stars BD +61°154 and BD +66°3471 show P Cygni profiles at H$\alpha$ but were not detected. There is possibly weak (~0.1 mJy) emission at the position of BD +61°154, but the significance level is only 3.7 $\sigma$, and it cannot clearly be differentiated from the background noise. Using the distances and flux upper limits in Table 2, and assuming a "typical" wind velocity of $\sim 300$ km s$^{-1}$, we obtain $3 \sigma$ upper limits on the mass-loss rate due to ionized winds of $M \leq 0.9 \times 10^{-7} M_\odot$ yr$^{-1}$ for BD +61°154 and $M \leq 1.3 \times 10^{-7} M_\odot$ yr$^{-1}$ for BD +66°3471. Although none of the A-type stars in our program were detected, it still appears likely that some Herbig Ae stars are radio sources (Güdel et al. 1989).

IV. CONCLUSIONS

We have detected radio continuum emission at low flux levels (0.1-1.9 mJy) in four out of 13 early-type PMS stars observed with the VLA. Three of the detected stars show evidence for winds or outflows (HD 259431, HD 200775, and MWC 1080), and the fourth detection (TY CrA) is a known X-ray source.

A picture is now emerging that indicates the presence of both thermal and nonthermal radio emission in early-type PMS stars. Thermal emission is dominant in the B9e star HD 200775 studied here, as well as in the B5-7e star LkHα 234 (Wilking, Mund, and Schwartz 1986). In both cases the spectral indices are positive, and there is observational evidence for winds and outflows. In contrast, the spectral index of the B9e star TY CrA is negative in the wavelength range 3.6-6 cm, and we have argued here that its radio emission is nonthermal. Güdel et al. (1989) have postulated that the radio emission of AB Aur is also nonthermal.

Further investigation into the origin of nonthermal radio emission in early-type PMS stars is warranted. If it can be shown that the emission is due to gyromagnetic processes, then previous arguments for the existence of magnetic fields in these stars (see Gnedin and Pogodin 1985) will be strengthened.

We thank Greg Taylor and Bill Junor of the VLA staff for assistance with data calibration. This work is supported by NASA grant NAG5-82 to the University of Colorado.

REFERENCES

No. 2, 1990

EARLY-TYPE PRE-MAIN-SEQUENCE STARS


ALEXANDER BROWN, JEFFREY L. LINSKY, AND STEPHEN L. SKINNER: Joint Institute for Laboratory Astrophysics, Campus Box 440, University of Colorado, Boulder, CO 80309-0440


© American Astronomical Society • Provided by the NASA Astrophysics Data System