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A RICH CLUSTER OF RADIO STARS IN THE ρ OPHIUCHI CLOUD CORES

JAMES A. LEOUS AND ERIC D. FEIGELSON
Department of Astronomy and Astrophysics, 525 Davey Laboratory, The Pennsylvania State University, University Park, PA 16802

PHILIPPE ANDRÉ[1]
National Radio Astronomy Observatory,[2] 949 North Cherry Avenue, Campus Building 65, Tucson, AZ 85721-0655

AND

THIERRY MONTMERLE
Service d'Astrophysique, DPhG/SAp, Centre d'Etudes Nucléaires de Saclay, 91191 Gif-sur-Yvette Cedex, France
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ABSTRACT

Deep 6 cm VLA observations of the central regions of the ρ Ophiuchi star-forming cloud reveal a concentration of faint stellar radio sources. A sensitivity better than 0.09 mJy is achieved, corresponding to 2.3×10^{15} ergs s^{-1} Hz^{-1}, a factor of 10–20 more sensitive than previous observations of the cloud (Stine et al.). In the northern molecular core, ρ Oph A, 22 sources are seen in a $13' \times 13'$ map centered on the embedded B star S1. Below 0.4 mJy, the source density is several times that expected from extragalactic sources. At least seven radio sources are associated with young stars: six are coincident with infrared sources, and one with a strong millimeter source at the base of a bipolar flow (André et al.). In the southern molecular core, ρ Oph E/F, 13 faint radio sources are detected; at least six are coincident with infrared stars. The low-mass stellar radio sources range in radio intensity from 0.2 to 3 mJy. These studies show that continuum radio emission far above levels present in main sequence stars is observed in one-third to one-half of low-mass pre–main-sequence stars. However, it is not clear whether the radio emission is generally thermal or nonthermal in origin.

Subject headings: nebulae: individual (ρ Ophiuchi) — stars: pre–main-sequence — stars: radio radiation

1. INTRODUCTION

Low-mass pre–main-sequence (PMS) stars are most frequently discovered and studied at optical, infrared, and X-ray wavelengths. Recently, however, several dozen have been found at centimeter radio wavelengths (e.g., Bieging, Cohen, & Schwartz 1984; Garay, Moran, & Reid 1987; André, Montmerle, & Feigelson 1987; O'Neal et al. 1990; other references in Herbig & Bell 1988). The relationship between PMS radio emission and their other properties is not always clear. Only a few cases possess the radio properties expected from simple optically thick thermal emission due to ionized T Tauri winds. Some may be thermal emission associated with collimated winds, but others are clearly nonthermal emission from enhanced solar-type magnetic activity (see reviews by Feigelson 1987; Feigelson, Giampapa, & Vrba 1991).

We report here the deepest radio continuum survey of a star-forming cloud obtained to date. Directed at the nearby ρ Ophiuchi star-forming cloud (distance ~ 160 pc) with a 5 σ sensitivity of ~ 90 μJy or better at 4.86 GHz, our observations can detect sources with luminosity densities $\geq 2.3 \times 10^{15}$ ergs s^{-1} Hz^{-1}. This is a factor of 10–20 more sensitive than earlier studies of the ρ Ophiuchi cloud (Falgarone & Gilmore 1981; Feigelson & Montmerle 1985; André et al. 1987; Stine et al. 1988), which had detected at least eight stellar radio sources or $\sim 10\%$ of the young star population. Our goals are to find the radio luminosity function of PMS stars and embedded young stellar objects (YSOs) and elucidate the evolutionary stages and properties associated with high levels of radio emission. This study is confined to two dense core regions of the ρ Ophiuchi cloud, known to contain many young objects from infrared surveys.

2. OBSERVATIONS

The two regions in the ρ Ophiuchi star-forming region were observed with the VLA at a wavelength of 6 cm (central frequency 4.866 GHz, total bandwidth 100 MHz) in a mixed C/D configuration. The northern field is centered on the early-type star S1 at $\alpha = 16^h23^m32\overset{s}{.}7$, $\delta = 24°16'44\overset{''}{.}0$, and includes the dense (peak density 5×10^5 cm^{-3}) molecular core ρ Oph A (see Loren, Wootten, & Wilking 1990 for core designations). The southern field is centered at $\alpha = 16^h24^m15\overset{s}{.}0$, $\delta = -24°32'15\overset{''}{.}0$ and lies within the lower density (peak density 6×10^4 cm^{-3}) molecular cores ρ Oph E and F. Figure 1 shows the location of these fields with respect to the molecular distribution. The fields contain 15 and 17 infrared sources, respectively, that are confirmed YSOs (Wilking, 1989, hereafter WLY), and many additional faint infrared sources (Barsony et al. 1990, henceforth BBRCG; Greene & Young 1991, hereafter GY). Several of the YSOs have also been seen in X-rays (Montmerle et al. 1983).

Observations were made on 1988 April 9 and 10. The total on-source exposures were about 5.3 hr for ρ Oph A and 8.2 hr for ρ Oph E/F. An additional 2.7 hr from a 1987 February 6 cm observation was concatenated with the ρ Oph A data base for a total on-source time of 8.0 hr. Antenna phases and gains were adjusted using the nearby calibrator 1622−297, after flux calibration based on 3C 286. Images were made and CLEANed using the task MX in NRAO's Astronomical Image Processing System (AIPS). We used "natural weighting" in the UV plane to get maximum sensitivity to weak sources (Sramek

[1] NRAO Jansky Fellow.

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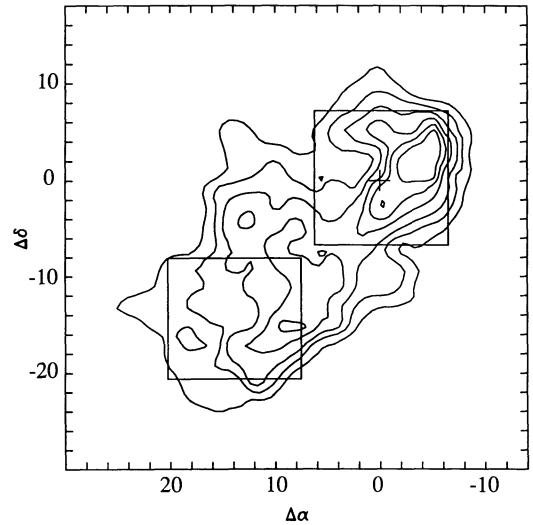

FIG. 1.—$C^{18}O(J = 2 \rightarrow 1)$ contours of molecular gas in the core region of the ρ Ophiuchi cloud (Wilking 1990). Boxes indicate the VLA fields described here. The cross shows the luminous star S1.

& Schwab 1986). The dynamic range of the ρ Oph A map was improved by a single pass of phase self-calibration; the ρ Oph E/F map was not affected by self-calibration.

The resulting maps, shown in Figures 2*a* and 2*b*, were made with 512 × 512 pixels covering an area 12$'$.8 × 12$'$.8, with synthesized beam width around 11$''$ × 5$''$. The root mean square (rms) noise levels are 18 μJy beam^{-1} for core A and 15 μJy beam^{-1} for core E/F. Each map was examined for radio sources, defined as centers of emission with peaks ≥5 times the local rms noise. We chose 5 σ to locate reliable radio sources without a priori knowledge of PMS star locations. Peak flux densities and positions were determined in three ways: parabolic fit to the local peak (AIPS program MAXFIT); least-squares fit to a two-dimensional Gaussian model (IMFIT); and integrated emission in a box around the peak (IMSTAT). For most sources, these three methods gave flux densities consistent within 20%, as expected from unresolved point sources. For a few sources, the Gaussian and integrated flux densities were ≫20% above the local peak strength. Most of these apparently extended sources lie far off-axis, where bandwidth smearing of the point-spread function is significant. One source is definitely extended and is probably a lobe associated with the bright extragalactic source BZ 6.

The resulting sources are listed in Tables 1 and 2 for the two fields. Within the primary beam, positions are accurate to better than 1 pixel or about ±0$''$.5. The fourth column gives the local peak flux density together with the rms noise level measured near the source. The fifth column gives the integrated flux density. All flux densities are corrected for primary beam attenuation.

3. STELLAR RADIO SOURCES

These faint radio sources were then compared to the lists of 2 μm sources given by WLY, BBRCG, and GY. WLY quote an uncertainty of "a few arcseconds" for the infrared sources. A coincidence was assigned if the radio position was within 5$''$ of a WLY source, resulting in nine associations with VLA sources. The survey of BBRCG covers only the E/F field of our survey, with infrared positions accurate to 15$''$. In addition to the five WLY sources in the ρ Oph E/F field, BBRCG source 18 lies within 5$''$ of VLA source 25. However, BBRCG identify this source with WL 14, which is ≥21$''$ from source 25, and GY do not find a second source. This identification is thus questionable. The new high-sensitivity survey by GY covers all of

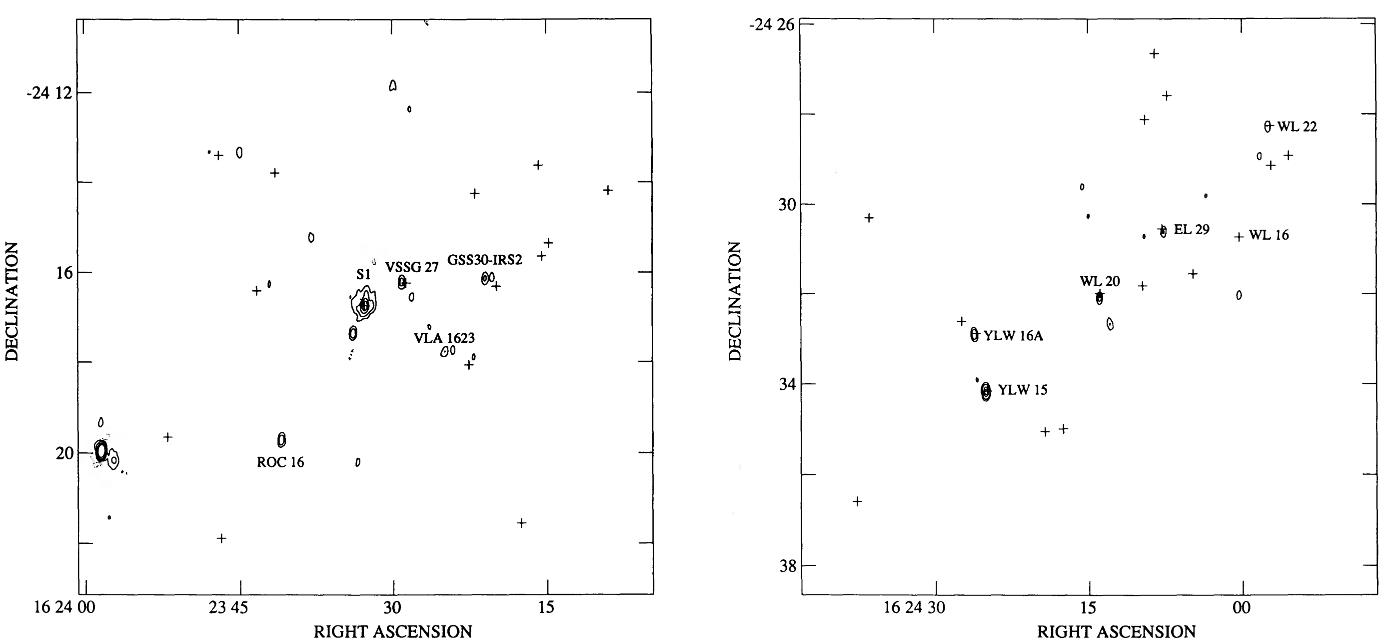

FIG. 2*a* FIG. 2*b*

FIG. 2.—Contour maps of the VLA fields. Stellar identifications are labeled. The crosses indicate the positions of stellar infrared sources from Wilking et al. (1989). (*a*) The northern Core A. Contour levels are −90, 90, 300, 1000, and 3000 μJy beam^{-1}. (*b*) The southern Cores E/F. Contour levels are −70, 70, 200, 800, and 1500 μJy beam^{-1}.

TABLE 1

SOURCES IN THE ρ OPHIUCHI A CORE

Number	R.A.	Decl.	$S_{6\,\mathrm{cm}}$ (μJy) Peak	Integrated	Notes[a]	Stellar Identification[b]
1............	16h23m20.s3	−24°16′06″.6	248 ± 24	297		...
2............	16 23 21.0	−24 16 07.9	506 ± 23	556		GSS 30 IRS 2, GY
3............	16 23 22.1	−24 17 54.4	158 ± 23	193		GY
4............	16 23 24.2	−24 17 44.1	228 ± 21	249		...
5............	16 23 24.9	−24 17 46.3	351 ± 20	388		VLA 1623−243E
6............	16 23 26.4	−24 17 12.8	126 ± 19	121		...
7............	16 23 28.2	−24 16 32.7	175 ± 18	208		...
8............	16 23 28.3	−24 12 22.1	261 ± 36	194		...
9............	16 23 29.1	−24 16 12.6	590 ± 18	579		VSSG 27 = YLW 36, GY
10............	16 23 29.9	−24 11 48.5	357 ± 41	707	1	...
11............	16 23 32.7	−24 16 44.4	7444 ± 18	11590	2	ROC 15 = SFAM 13, GY; S1
12............	16 23 33.4	−24 20 11.7	203 ± 27	256		...
13............	16 23 33.9	−24 17 21.1	773 ± 18	784		...
14............	16 23 38.0	−24 15 12.8	177 ± 20	244		...
15............	16 23 40.9	−24 19 42.4	1272 ± 27	1268		ROC 16, GY
16............	16 23 42.0	−24 16 14.2	140 ± 21	148		...
17............	16 23 45.0	−24 13 19.4	543 ± 35	572		...
18............	16 23 48.0	−24 13 20.2	223 ± 40	259		GY
19............	16 23 57.2	−24 20 09.9	1952 ± 84	5374	3	...
20............	16 23 57.8	−24 21 25.4	824 ± 151	1792	1	...
21............	16 23 58.4	−24 19 57.8	79266 ± 91	86222	1, 4	...
22............	16 23 58.5	−24 19 21.2	599 ± 78	1030	1	...

[a] NOTES.—(1) Appears extended, possibly due to bandwidth smearing. (2) Core-halo structure; see André et al. 1988 for details. (3) Definitely extended. (4) Radio source BZ 6 = ROC 19 = SFAM 20, established by Stine et al. 1988 to be extragalactic.

[b] ROC and SFAM are the previous VLA radio studies from André, Montmerle, & Feigelson 1987 and Stine et al. 1988. GY is the infrared survey of Green & Young 1990. Other designations and aliases are from WLY (Wilking, Lada, & Young 1989, Table 4).

the E/F field and most of the A field with a limiting magnitude of $K = 15$, and a positional accuracy of better than a few arcseconds. It confirms seven identifications with WLY and BBRCG sources and adds five infrared identifications. One of these is IRS 2 in the infrared reflection nebula GSS 30. This source, which probably does not excite the nebula, is discussed in detail by Castelaz et al. (1985). Omitting BBRCG 18, we have 12 VLA sources spatially coincident with infrared sources (see the last column of Tables 1 and 2).

In addition to the analysis above based on the list of radio sources with ≥ 5 times the map noise level, we have searched the positions of infrared objects for radio sources of lower significance. We find eight locations with radio fluxes between 3.0 and 5.0 × local rms within $\pm 5''$ of 2 μm sources and not listed in Tables 1 or 2. These locations, flux densities (including correction for primary beam attenuation), and associated infrared sources are listed in Table 3. We suspect, but can not confirm, that most of these are true radio sources physically associated with young stars. Others will be chance coincidences, radio noise peaks, or noncluster infrared sources. Due to these uncertainties, we do not include these candidates in the source counts (above) or luminosity function (below).

Our A and E/F core fields are also included in the *IRAS* 12 μm map and source lists of WLY. This provides an

TABLE 2

SOURCES IN THE ρ OPHIUCHI E/F CORE

Number	R.A.	Decl.	$S_{6\,\mathrm{cm}}$ (μJy) Peak	Integrated	Stellar Identification[b]
23[a]...........	16h23m57.s5	−24°28′16″.2	599 ± 41	782	WL 22 = YLW 4 = IRS 27, GY
24...........	16 23 58.3	−24 28 55.6	322 ± 33	310	BBRCG 18?
25...........	16 24 00.3	−24 32 01.7	215 ± 20	242	...
26...........	16 24 03.5	−24 29 48.1	137 ± 21	104	GY
27...........	16 24 07.6	−24 30 37.0	271 ± 16	303	EL 29 = WL 15 = C 15 = YLW 7 = BBRCG 23, GY
28...........	16 24 09.5	−24 30 43.7	110 ± 16	69	...
29...........	16 24 12.9	−24 32 39.4	213 ± 14	281	...
30...........	16 24 13.9	−24 32 04.9	309 ± 14	354	WL 20 = YLW 11 = BBRCG (31 + 33), GY
31...........	16 24 15.0	−24 30 15.9	98 ± 16	97	...
32...........	16 24 15.6	−24 29 38.3	145 ± 18	148	...
33...........	16 24 25.1	−24 34 09.9	2845 ± 19	3264	YLW 15 = IRS 43 = ROC 24, GY
34...........	16 24 26.0	−24 33 53.7	112 ± 19	119	...
35...........	16 24 26.2	−24 32 53.1	780 ± 17	824	YLW 16A = IRS 44 = BBRCG 49, GY

[a] Appears extended, possibly due to bandwidth smearing.

[b] ROC is the previous VLA radio study from André, Montmerle, & Feigelson 1987. BBRCG and GY are the infrared surveys of Barsony et al. 1989, Table 1 and Green & Young 1990. Other designations and aliases are from WLY (Wilking, Lada, & Young 1989, Table 4).

TABLE 3

POSSIBLE ADDITIONAL SOURCES COINCIDENT WITH INFRARED STARS

Number	R.A.	DECL.	$S_{6\ cm}$ (μJy)	Stellar Identification
1...........	$16^h23^m15^s.4$	−24°15′37″.5	143 ± 35	GSS 29 = C 13 = EL 18 = S 28
2...........	16 23 36.2	−24 16 15.4	61 ± 18	GY
3...........	16 23 43.6	−24 16 24.7	85 ± 22	GY
4...........	16 23 53.1	−24 20 16.6	183 ± 58	GY
5...........	16 24 11.1	−24 34 53.1	67 ± 19	GY
6...........	16 24 17.6	−24 35 00.1	72 ± 18	SR 12(A + B) = ROX 21 = IRS 40, GY
7...........	16 24 31.0	−24 26 46.0	317 ± 72	GY
8...........	16 24 37.6	−24 32 36.5	155 ± 37	GY

opportunity to look for counterparts at longer infrared wavelengths. By using the 2–12 μm spectral index, it is possible, in principle, to estimate the infrared classification (Lada 1987) and hence the nature of the identified VLA sources. When seen at 12 μm, the VLA fields A and E/F are very different. Field A is relatively smooth and completely dominated by the bright emission of S1 (140 Jy), which prevents any further identification of the *IRAS* sources with VLA or near-IR sources in this field. By contrast, field E/F is rich in fainter 12 μm sources (< 30 Jy), but because the *IRAS* beam is so extended (210″ in R.A., 45″ in decl.), there is some confusion which inhibits precise identifications. Our sources 23 and 24 lie within the beam of IRAS 4; the same situation holds for sources 26 and 27 (IRAS 7), 29 and 30 (IRAS 11), and 33 and 34 (IRAS 15). Source 35, on the other hand, is the only VLA source to lie within the beam of IRAS 16, identified with YLW 16A. Interestingly, this makes it a class I source ("protostar"), which is otherwise known to excite a weak bipolar flow (Terebey, Vogel, & Myers 1989), a situation similar to our source 5, VLA 1623 (see below). Clearly, the issue of the 12 μm source identification cannot be settled now and must wait until results from the newly available 10 μm cameras.

Some of the unidentified radio sources may be young stellar objects which are either to obscured or too faint to be detected by infrared surveys to data. This population would consist of sources remaining after background extragalactic and known stars are counted. The number of extragalactic sources is estimated using the log N–log S formalism given in the appendix to Rodríguez et al. (1989), adjusted to our limiting sensitivities and field sizes. These calculations show that approximately 18 of the 35 radio sources in Tables 1 and 2 are probably extragalactic. Our observed source distribution, this predicted extragalactic source population, and the reliable stellar identifications (*hatched region*) described above are compared in Figure 3. While the observed and predicted distributions agree in the higher flux density bins, there is an excess of unidentified sources in the bins with $S_{6\ cm} < 0.4$ mJy. There are about six sources which are neither infrared young stars or extragalactic radio sources, and therefore may be radio-discovered young stellar objects. This result is subject to both the uncertainties in the log N–log S curve and the statistics of small numbers. This comparison was based on the peak flux densities; no qualitative difference is found when integrated fluxes are used.

There is one clear example of a radio-discovered YSO in our fields. Millimeter observations performed with the IRAM 30 m telescope demonstrate that VLA source 5 is a young stellar

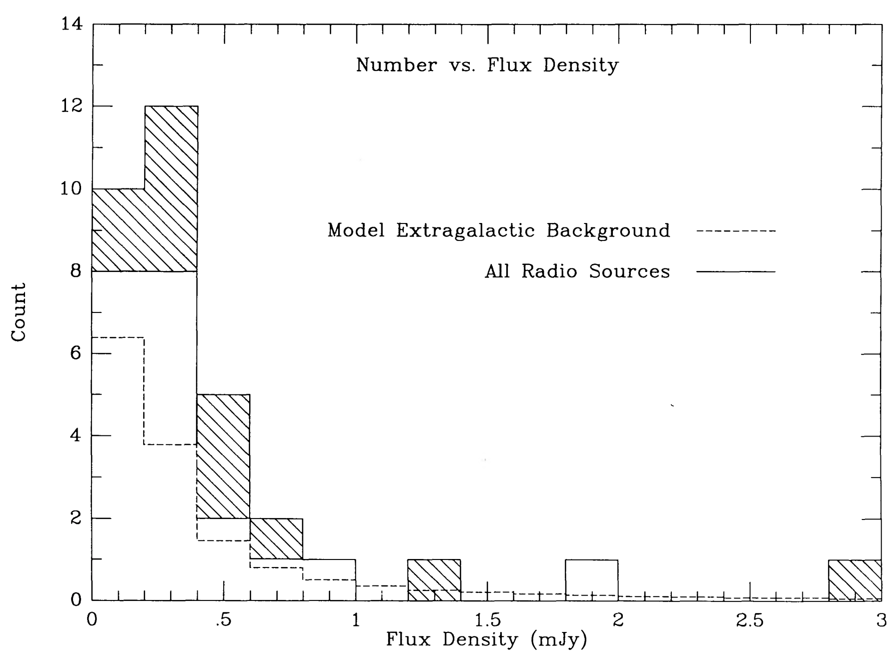

FIG. 3.—Comparison of observed and expected source counts. Two sources brighter than 3 mJy (BZ 6 and S1) lie off the graph. *Solid line:* Observed sources (Tables 1 and 2). *Dashed line:* Predicted extragalactic sources. *Hatched region:* Stellar identifications.

object with $S_{1.3\ \mathrm{mm}} = 900$ mJy but $K > 17$, lying at the center of symmetry of a highly collimated CO bipolar flow (André et al. 1990a, b). It is interpreted to be a very young star which is heavily obscured by an edge-on dusty disk. Our study shows two faint radio sources, with $S_{6\ \mathrm{cm}} = 0.23 \pm 0.02$ and 0.35 ± 0.02 mJy separated by 11″. The brighter source (designated VLA 1623−243E) coincides, within the positional uncertainties, with the millimeter peak and we associate it with the YSO powering the outflow.

Two identified radio sources merit specific comment. First, source 11 coincides with the luminous embedded B star, S1, which emits both thermal radio emission from a compact H II region and nonthermal radio emission from a giant magnetosphere. It is an unusual source with a VLBI component and circular polarization and is discussed in detail elsewhere (André et al. 1988; André et al. 1991).

We also note that source 15 was suspected to be a stellar object on the basis of its ascending radio frequency spectrum in our earlier radio study (André et al. 1987). This suspicion is now confirmed by its detection as a faint 2 μm source (GY). Very recent $C^{34}S(2 \rightarrow 1)$ observations with the NRAO 12 m telescope (P. André & R. B. Loren 1990, unpublished observations) further indicate that this source is associated with dense molecular gas.

4. DISCUSSION

By increasing the sensitivity by a factor of 20, we have increased the initial sample of radio-detected stars in these two cloud core fields from 3 to 13. Specifically, the previously identified stars are VLA sources 11, 15 and 33 (André et al. 1987; Stine et al. 1988), and the new identifications are Sources 2, 3, 5, 9, 18, 23, 26, 26, 30, and 35. In addition, up to eight other infrared sources may be faint radio sources (Table 3), and up to six radio sources may be stars not yet detected at infrared wavelengths (Fig. 3). Thus, the 13 confirmed identifications in the cloud cores may be only the brighter half of the accessible population of radio stars.

Though particularly rich, this cluster of radio stars in the inner ~1 pc of a star-forming cloud is not unique. VLA observations of a ~0.2 pc region around the Orion Nebula Trapezium reveals nearly 30 compact sources (Garay et al. 1987; Churchwell et al. 1987). About half are unresolved (<12 AU diameter) and variable and are probably not compact H II regions. In other regions, the presence of several radio sources may be indicative of the existence of other rich clusters of fainter sources. For instance, two radio variable PMS stars are found within a parsec of LkHα 101 (Becker & White 1988), two or more variable sources are found in the R CrA cloud core (Brown 1987), and one variable source is found among a group of H II regions in Cepheus A (Hughes 1988). Radio continuum sources are also commonly seen associated with the sources of bipolar molecular outflows (Rodríguez et al. 1989, and references therein). Most of these studies attain sensitivities $\gtrsim 10^{16}$ ergs s^{-1} Hz^{-1}. Our findings suggest that several times more radio PMS emitters will be seen in these regions if sensitivities of 2×10^{15} ergs s^{-1} Hz^{-1} could be achieved in these other clouds.

Because of our increased number of young stellar radio sources, it becomes possible for the first time to look for some global, empirical properties. Using the Kaplan-Meier maximum likelihood estimator that includes nondetections (Feigelson & Nelson 1985), we calculate the radio luminosity function for the WLY stars in the two cores. (A similar calculation based on the BBRCG or GY infrared samples may be biased, since these samples may have significant contamination of field stars.) The luminosity function (Fig. 4) shows that $9 \pm 5\%$ of young stars in the ρ Ophiuchi cloud have a luminosity above about 2.5×10^{16} ergs s^{-1} Hz^{-1}, and $33\% \pm 10\%$ have radio luminosity $\gtrsim 2.5 \times 10^{15}$ ergs s^{-1} Hz^{-1}. This luminosity function is based on the peak flux densities; the function is slightly extended at the higher luminosity levels when integrated flux densities are used.

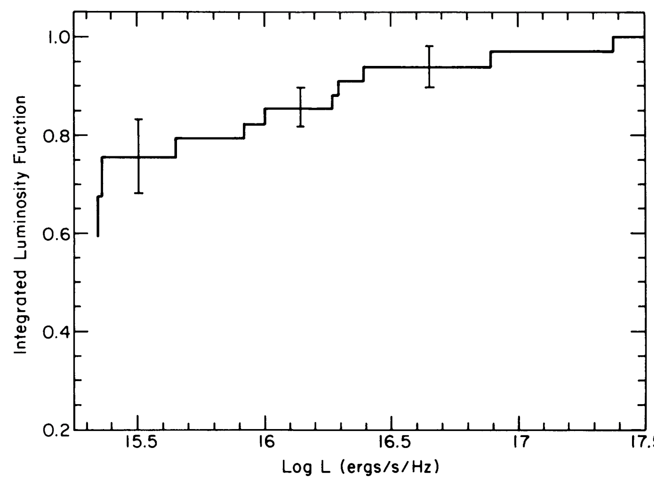

FIG. 4.—The 6 cm maximum likelihood luminosity function of the WLY sources in both fields. The error bars give analytic estimates of the 1 σ uncertainties (Feigelson & Nelson 1985).

The radio luminosity function of embedded pre-main-sequence stars derived here appears quite similar to the luminosity function of magnetically active post-main-sequence RS CVn stars (Drake, Simon, & Linsky 1989). Also, the fraction emitting above $\sim 10^{16}$ ergs s^{-1} Hz^{-1} in the ρ Ophiuchi embedded stars is identical to that found for Taurus-Auriga "weak" T Tauri stars (O'Neal et al. 1990). These similarities hint that magnetic activity may also be the principal source of radio emission in the embedded ρ Ophiuchi stars. It further implies that classical T Tauri stars and protostars, in contrast to magnetically active weak T Tauri stars, are not significant contributors to the radio population at these high radio luminosities.

Finally, we note that a few of our sources occur in close pairs. Sources 1 and 2 (GSS 30 IRS 2) are separated by ~10″; sources 4 and 5 (VLA 1623−243E and W, respectively) are separated by ~11″. For this last source, which excites an unusually young and collimated molecular outflow (André et al. 1990a), this is reminiscent of the double protostellar radio source IRAS 16293 (Walker et al. 1988), elsewhere in ρ Ophiuchi complex, but far from the dense core. On the other hand, GSS 30 IRS 2 does not appear to excite a molecular outflow, so a meaningful connection between double centimeter radio sources and molecular outflows is uncertain.

5. CONCLUSIONS

Our survey of radio emission from pre-main-sequence stars in the ρ Ophiuchi cloud cores has shown that radio emission is very common at levels down to luminosity densities $\gtrsim 2.5 \times 10^{15}$ ergs s^{-1} Hz^{-1}. We detect 13 confirmed, and up to 14 possible additional, radio pre-main-sequence stars within a 1 pc^2 area of the star-forming cores. The confirmed detections constitute at least 30% of the known young stellar population;

in fact, this fraction reaches $\sim 50\%$ in the E/F core. For the remaining, unidentified radio sources, log N–log S counts show that most are extragalactic. But a few may be deeply embedded young stellar objects (e.g., VLA 1623) which are detected *only* at radio frequencies and have not yet been found in infrared surveys.

Finally, we note that the physical processes of the radio emission are not yet clear. Conceptually, we suggest that young radio stars with disks (indicated by strong infrared and/or millimeter excesses) are more likely to be thermal radio emitters, and stars without disks are more likely to be nonthermal emitters. The tentative correlation between 6 cm flux and 1.3 mm flux presented by André et al. (1990b) points to the link between disks and thermal radio emission. Thermal models can in principle be confirmed by the detection of spatial extent to the radio emission, though this may require VLBI measurements of extremely faint sources. On the other hand, "weak T Tauri" radio emission, such as seen in DoAr 21 and HD 283447, is highly variable, spatially compact, and clearly nonthermal in origin (e.g., Feigelson & Montmerle 1985; Phillips, Lonsdale, & Feigelson 1991). A considerable number of similar nonthermal PMS radio emitters is emerging from various studies (e.g., Stine et al. 1988; O'Neal et al. 1990). The similarity of the radio luminosity function derived here and that of nonthermal RS CVn systems suggests that many of the stars found here are nonthermal. Given these disparate indications, it is quite possible that some of the sources in the ρ Ophiuchi core are thermal and others are nonthermal. To better illuminate these physical processes, spectral, variability, and VLBI studies of ρ Ophiuchi radio stars are being pursued.

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