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MULTIFREQUENCY VLA OBSERVATIONS OF RADIO CONTINUUM FROM IRAS 16293–2422

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ABSTRACT

Using the VLA at 20, 6, 2, and 1.3 cm, we observed the cold infrared source IRAS 16293–2422. Our data allow a determination of the spectral indices of the components A and B. IRAS 16293–2422A, which is known from higher angular resolution data to consist of at least two subcomponents, has a spectral index $\alpha = 0.6 \pm 0.1$, consistent with the subcomponent sources being partially optically thick H II regions or ionized outflows. On the other hand, IRAS 16293–2422B has a very steep spectral index, $\alpha = 2.1 \pm 0.2$ between 6 and 2 cm and $\alpha = 3.2 \pm 0.5$ between 2 and 1.3 cm. The spectral index from the 6 and 2 cm data is consistent with an optically thick H II region, and the unusually large spectral index between 2 and 1.3 cm suggests that the 1.3 cm flux may have a contribution from dust emission. We have also monitored the region at 2 cm in five different occasions over a period of 14 months. We did not detect evidence of variability within the observational uncertainty.

Subject headings: infrared: sources — radio sources: spectra — stars: pre–main-sequence — nebulae: H II regions

1. INTRODUCTION

IRAS 16293–2422 is a cold infrared source located in the ρ Ophiuchi molecular cloud complex. The dense molecular gas associated with IRAS 16293–2422 has been the subject of recent studies by Walker et al. (1986, 1988), Mundy, Wilking, & Myers (1986), Wootten & Loren (1987), Menten et al. (1987), Mundy, Wootten, & Wilking (1990), and Mizuno et al. (1990). Mundy et al. (1986) also mapped interferometrically the 2.7 mm continuum emission from the surrounding dust and concluded that the spectrum is well fitted by a $\nu^{+1.5 \pm 0.5}$ emissivity law and a dust temperature of 41 ± 2 K. Their fits imply a total luminosity of $27 \pm 4\ L_\odot$ and a mass of gas and dust in the range of 0.9–6.0 $M_\odot$. The 2.7 mm continuum map of Mundy et al. (1986) shows that the emission arises from a double source with peaks separated by $\sim 5''$ along a NW-SE axis. Wootten (1989) made VLA observations at 6 and 2 cm of the region, detecting two continuum sources coincident in position ($< 1''$) with the 2.7 mm peaks mapped by Mundy et al. (1986). Wootten (1989) refers to these sources as IRAS 16293–2422A (the southeast component) and IRAS 16293–2422B (the northwest component) and resolves IRAS 16293–2422A into two subcomponents separated by $\sim 0''.3$.

The nature of radio continuum emission associated with young, low-luminosity stars remains unclear. The possibility of a classic, photoionized H II region seems to be ruled out since the required ionizing photon fluxes are orders of magnitude larger than those expected from the associated stars (Rodríguez et al. 1989). Torrelles et al. (1985) proposed that the required ionizing photons are produced by hot, shocked gas that results from the interaction of a stellar wind with surrounding material. André, Montmerle, & Feigelson (1987) and Stine et al. (1988) have shown that in some sources the radio continuum emission has a time-variable, nonthermal nature and may be produced by extended magnetic structures associated with the star.

IRAS 16293–2422 is one of the brightest radio continuum sources among the young, low-luminosity stars, and, in an attempt to better understand the nature of its radio continuum emission, we undertook a VLA study of the region that includes observations at 20, 6, 2, and 1.3 cm, as well as time monitoring at 2 cm.

2. OBSERVATIONS

The observations were made with the VLA of NRAO,[1] and the observational parameters are summarized in Table 1. The region was observed with an effective bandwidth of 100 MHz and the absolute amplitude calibrator was 3C 286 for which fluxes of 14.51 Jy (20 cm), 7.41 Jy (6 cm), 3.48 Jy (2 cm), and 2.53 Jy (1.3 cm) were adopted. The phase calibrators and their bootstrapped fluxes are also given in Table 1. The observations were edited and calibrated following the standard VLA procedures. Cleaned maps were obtained with the program MX of AIPS. All maps were made with uniform weighting, except for the 1.3 cm data, where natural weighting and tapering was used in order to match approximately the angular resolution of the 2 cm map made from the C-configuration observations.

In Table 1 we present the flux densities obtained from our observations made at various wavelengths and epochs. The flux densities were obtained from Gaussian fittings to the map components. We first used the set of four observations made at

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[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

TABLE 1

OBSERVATIONS OF THE IRAS 16293 − 2422 REGION

EPOCH	CONFIGURATION	BAND (cm)	ON-SOURCE INTEGRATION TIME (minutes)	PHASE CALIBRATOR	BOOTSTRAPPED FLUX (Jy)	SYNTHESIZED BEAM		FLUX DENSITIES[a] (mJy)	
						HPFW (″)	p.a. (°)	IRAS 16293 − 2422A	IRAS 16293 − 2422B
1987 Jun 6–8	D	20	26	1643 − 223	1.76 ± 0.03	60.0 × 43.5	−33	1.68 ± 0.40	...[b]
1987 Jun 6–8	D	6	52	1622 − 297	1.83 ± 0.03	19.2 × 10.9	0	2.90 ± 0.14	...[b]
1987 Jun 6–8	D	2	463	1622 − 297	1.56 ± 0.05	5.9 × 3.1	−1	6.12 ± 0.22	2.38 ± 0.22
1988 Mar 27	C	6	24	1622 − 297	1.78 ± 0.02	5.7 × 3.4	−19	3.64 ± 0.18	...[b]
1988 Mar 27	C	2	40	1622 − 297	1.19 ± 0.03	2.2 × 1.1	−11	4.84 ± 0.28	2.56 ± 0.28
1988 Mar 27	C	1.3	46	1622 − 297	0.94 ± 0.06	2.3 × 1.3[c]	−3	6.30 ± 1.00	9.56 ± 1.00
1988 Jul 17	D	2	84	1622 − 297	1.07 ± 0.05	7.0 × 3.3	6	6.61 ± 0.42	2.53 ± 0.42
1988 Aug 10	D	2	91	1622 − 297	1.21 ± 0.06	7.0 × 3.4	−3	7.37 ± 0.40	2.02 ± 0.40
1988 Aug 20	D	2	91	1622 − 297	1.33 ± 0.06	6.8 × 3.3	−9	7.04 ± 0.32	1.62 ± 0.32

[a] Obtained from Gaussian fits to the two components. Errors quoted are 2 times the rms noise of the map.

[b] Only one component fitted. All the flux attributed to the A component.

[c] Obtained with natural weighting and a (u, v) tapering of 150 kλ.

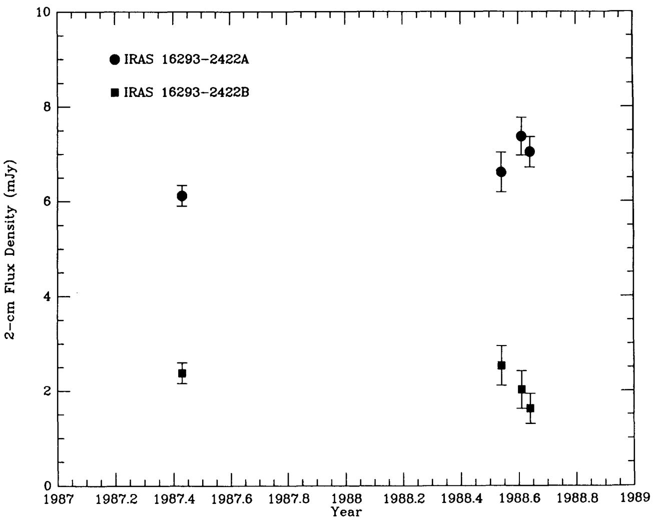

FIG. 1.—Flux densities from the 2 cm, D-configuration VLA data as a function of time.

2 cm in the D-configuration to search for possible time variability, a characteristic that would favor a very compact, nonthermal nature for the sources. In Figure 1 we show the flux densities as a function of time. Within the observational uncertainty, we conclude that the two sources do not show significant time variation on scales that go from several days to about a year. We also searched for rapid variability dividing our 1987 June, 2 cm data into six bins of approximately 2 hr each. We found no significant flux changes (at the 20% level), a result that suggests that there is no time variability on time scales of hours. Finally, we searched unsuccessfully for linear and circular polarization in the 6 and 2 cm data of 1987 June, setting upper limits of typically 10%.

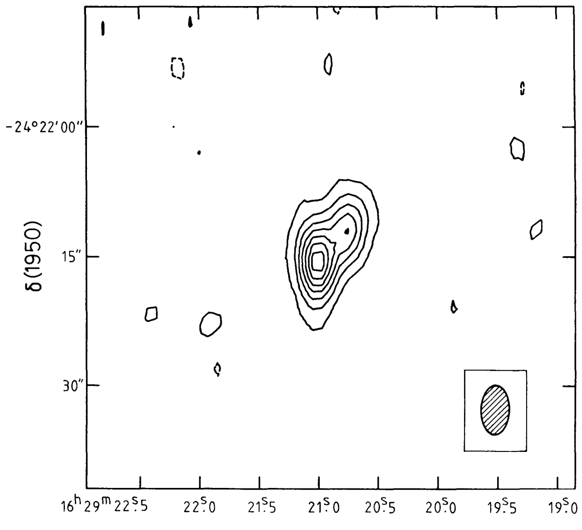

FIG. 2.—Cleaned VLA map at 2 cm (D-configuration) of the IRAS 16293−2422 region. Contours are −1, 1, 3, 5, 7, 9, 11, and 13 times 0.3 mJy beam^{-1}. The half-power contour of the beam is also shown.

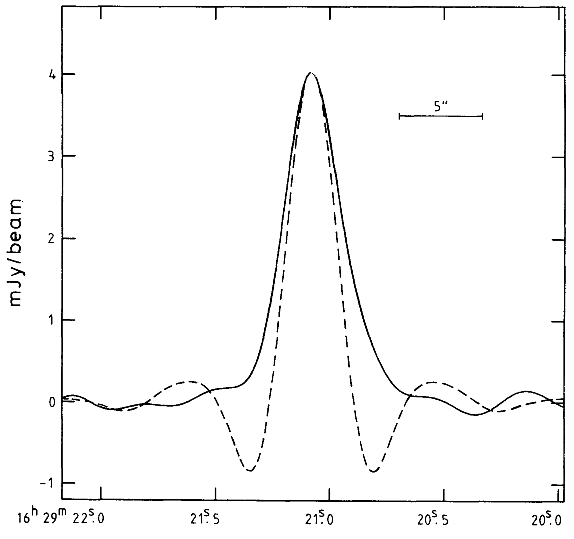

FIG. 3.—Cuts at a fixed declination ($\delta = -24^\circ22'15''.2$) across IRAS 16293−2422A (*solid line*) and the beam (*broken line*) for the 2 cm, D-configuration data. Note that the source appears to be significantly more extended than the beam.

A map made with the 2 cm, D-configuration data of 1987 June is shown in Figure 2. We note that while the 2 cm, D-configuration data give consistently flux densities of 6 to 7 mJy for IRAS 16293−2422A, the 2 cm, C-configuration observations made in 1988 March give a lower value of 4.8 mJy. We believe that this discrepancy is due to the presence of extended emission in association with IRAS 16293−2422A that is resolved out in our C-configuration observations. Wootten (1989), from 2 cm, A-configuration data with an angular resolution of about 0″.1, gives a total flux (the sum of subcomponents A1 and A2, separated 0″.3) of 4.6 mJy, consistent with our C-configuration determination. The presence of extended emission in IRAS 16293−2422A is evident in Figure 3, where we show cuts across the source and beam in the east-west direction. These cuts were made in a map where IRAS 16293−2422B had been subtracted as a point source (this source appears unresolved in our data). A Gaussian fit to IRAS 16293−2422A gives a deconvolved size of $\sim 2''$ for the source. At present it is unknown if this extended emission is due to a halo surrounding one or both subcomponents A1 and A2 or to the existence of weaker, yet undetected subcomponents.

3. NATURE OF THE RADIO SOURCES

In order to discuss the nature of the radio sources, we will use the 6, 2, and 1.3 cm fluxes available at similar angular resolution ($\sim 1''$), to determine spectral indices. We will then use the 6 cm fluxes of Wootten (1989) made in the A/B- and B/C-configurations, and the 2 and 1.3 cm fluxes obtained by us in the C- and D-configurations. In Figure 4 we show the resulting spectra. The fluxes for IRAS 16293−2422A are well fitted with a power law with spectral index of $\alpha = 0.6 \pm 0.1$, in agreement with the value of 0.6 expected for an ionized, isothermal stellar wind (Panagia & Felli 1975), or with a partially optically thick H II region. Our 20 cm data, although at lower angular resolution, are consistent with this spectral index if all the flux is attributed to IRAS 16293−2422A. If we interpret IRAS 16293−2422A as a compact H II region that is becoming

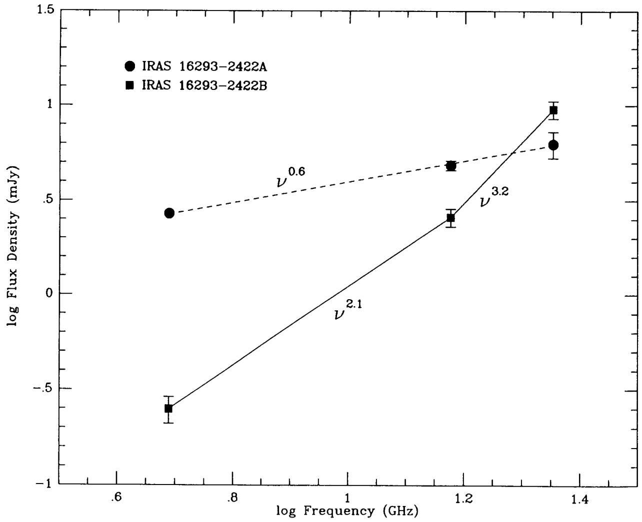

FIG. 4.—Spectra of IRAS 16293−2422A and IRAS 16293−2422B from the 6, 2, and 1.3 cm data with angular resolution of ∼1″. The 6 cm measurements are from Wootten (1989) and the 2 and 1.3 cm measurements are from this paper.

optically thin at a few cm and assume a distance of 160 pc, we find that an ionizing flux of $N_i \simeq 1.2 \times 10^{43}$ s^{-1} is required to maintain the H II region. This ionizing flux could be provided by a B4 ZAMS star, with $L \simeq 800\ L_\odot$ (Thompson 1984). However, the total IR luminosity of the region is only 27 $L_\odot$ (Mundy et al. 1986). The discrepancy is often found in regions of low-mass star formation. Radio sources that appear to be compact H II regions are commonly associated with stars of a few tens of $L_\odot$ or even less, which cannot provide the required ionizing fluxes. Curiel et al. (1989) have compiled a list of 21 radio sources of this type.

We now turn our discussion to IRAS 16293−2422B. Its spectral index from the 6 and 2 cm data is $\alpha = 2.1 \pm 0.2$, consistent with an optically thick H II region. Interestingly, the spectral index from the 2 and 1.3 cm data is even steeper, $\alpha = 3.2 \pm 0.5$. Our 2 and 1.3 cm maps of the region (Fig. 5) show that the flux of IRAS 16293−2422B rises rapidly with frequency. Curiel, Cantó, & Rodríguez (1987) have shown that ionized regions with electron temperature gradients can show spectral indices larger than 2.

An alternative explanation is that the 1.3 cm flux has a contribution from dust emission. We now discuss if this suggestion is consistent with what is known of IRAS 16293−2422B. If we assume that at 1.3 cm the free-free emission continues increasing as the frequency squared, we conclude that of the 9.6 mJy measured at this wavelength, ∼6.1 mJy can be attributed to the emission from the ionized gas. Then ∼3.5 ± 1.0 mJy could be due to dust emission. At 2.7 mm, Mundy et al. (1986) obtain a flux density of ∼300 mJy for IRAS 16293−2422B. Assuming that an emissivity law with a $\nu^{+1.5\pm0.5}$ dependence can be extrapolated to the cm range and that we have optically thin dust emission, we expect a flux density from dust emission of $1.2^{+1.5}_{-0.6}$ mJy at 1.3 cm. Our determination of ∼3.5 ± 1.0 mJy is then approximately consistent with an emissivity law with a $\nu^{+1.0}$ dependence. Beckwith et al. (1990) and Weintraub, Sandell, & Duncan (1989) have found that at mm wavelengths the index of the emissivity power law can go from 0.0 to 1.5. André et al. (1990) have suggested that VLA 1623, another source in the ρ Oph cloud, also has significant dust emission in the cm regime.

4. CONCLUSIONS

We observed at 20, 6, 2, and 1.3 cm with the VLA the region associated with IRAS 16293−2422. Our 2 cm monitoring of the region shows no significant time variability over a scale of several hours to about a year. The sources in the region show no circular or linear polarization at a level of 10%.

IRAS 16293−2422A has a spectral index of ∼0.6 from 6 to 1.3 cm, a value consistent with an ionized outflow or with a partially optically thick H II region. IRAS 16293−2422B has a spectral index of ∼2.1 between 6 and 2 cm and of ∼3.2 between 2 and 1.3 cm. This last spectral index suggests that the 1.3 cm flux may have a contribution from dust emission.

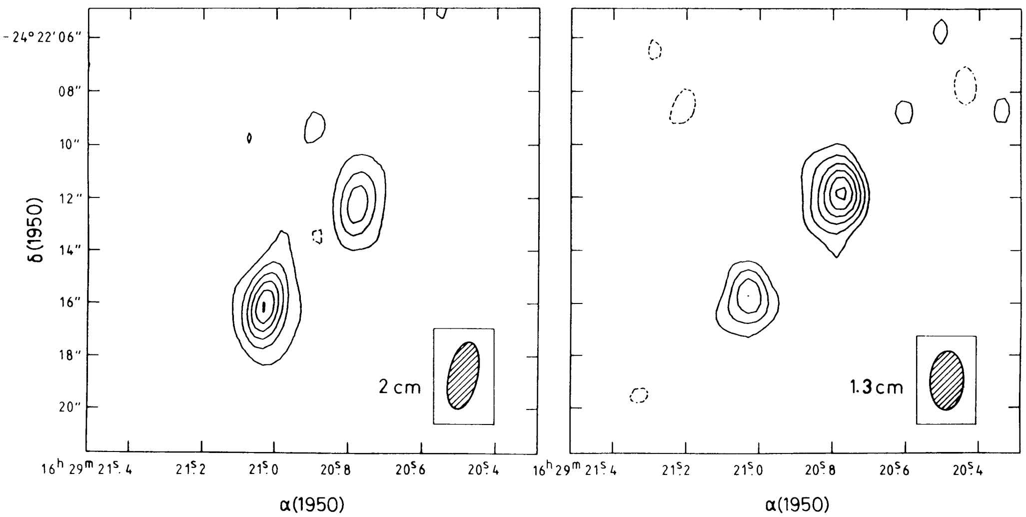

FIG. 5.—Maps of IRAS 16293−2422 at 2 (*left*) and 1.3 cm (*right*) made from the C- and D-configurations data. The half-power contour of the beams are also shown. Contours are −1, 1, 3, 5, 7, 9, and 11 times 0.4 mJy beam^{-1} for the 2 cm map and −3, 3, 5, 7, 9, 11, and 13 times 0.5 mJy beam^{-1} for the 1.3 cm map. Note that at 2 cm IRAS 16293−2422A is brighter than IRAS 16293−2422B, while at 1.3 cm IRAS 16293−2422B is brighter than IRAS 16293−2422A.

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REFERENCES

André, Ph., Montmerle, T., & Feigelson, E. D. 1987, AJ, 93, 1182
André, Ph., Montmerle, T., Feigelson, E. D., & Steppe, H. 1990, preprint
Beckwith, S. V. W., Sargent, A. I., Chini, R. S., & Güsten, R. 1990, AJ, 99, 924
Curiel, S., Cantó, J., & Rodríguez, L. F. 1987, Rev. Mexicana Astr. Ap, 14, 595
Curiel, S., Rodríguez, L. F., Cantó, J., Bohigas, J., Roth, M., & Torrelles, J. M. 1989, Ap. Letters Comm., 27, 299
Menten, K. M., Serabyn, E., Güsten, R., & Wilson, T. L. 1987, A&A, 177, L57
Mizuno, A., Fukui, Y., Iwata, T., Nozawa, S., & Takano, T. 1990, ApJ, 356, 184
Mundy, L. G., Wilking, B. A., & Myers, S. T. 1986, ApJ, 311, L75
Mundy, L. G., Wootten, H. A., & Wilking, B. A. 1990, ApJ, 352, 159
Panagia, N., & Felli, M. 1975, A&A, 39, 1
Rodríguez, L. F., Myers, P. C., Cruz-González, I., & Terebey, S. 1989, ApJ, 347, 461
Stine, P., Feigelson, E. D., André, Ph., & Montmerle, T. 1988, AJ, 96, 1394
Thompson, R. I. 1984, ApJ, 283, 165
Torrelles, J. M., Ho, P. T. P., Rodríguez, L. F., & Cantó, J. 1985, ApJ, 288, 595
Walker, C. K., Lada, C. J., Young, E. T., Maloney, P. R., & Wilking, B. A. 1986, ApJ, 309, L47
Walker, C. K., Lada, C. J., Young, E. T., & Margulis, M. 1988, ApJ, 332, 335
Weintraub, D. A., Sandell, G., & Duncan, W. D. 1989, ApJ, 340, L69
Wootten, A. 1989, ApJ, 337, 858
Wootten, A., & Loren, R. B. 1987, ApJ, 317, 220