VERY LARGE ARRAY OBSERVATIONS OF CANDIDATE HIGH-MASS PROTOSTELLAR OBJECTS AT 7 MILLIMETERS

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ABSTRACT

We present radio-continuum observations at 7 mm made using the Very Large Array toward three massive star-forming regions thought to be in very early stages of evolution, selected from the 2002 sample of Sridharan et al. Emission was detected toward all three sources (IRAS 18470+0044, IRAS 19217+1651, and IRAS 23151+5912). We find that in all cases the 7 mm emission corresponds to thermal emission from ionized gas. The regions of ionized gas associated with IRAS 19217+1651 and IRAS 23151+5912 are hypercompact, with diameters of 0.009 and 0.0006 pc and emission measures of \(7 \times 10^3\) and \(2.3 \times 10^9\) pc cm\(^{-6}\), respectively.

Key words: H\(\pi\) regions — stars: early-type — stars: formation

1. INTRODUCTION

One of the key challenges at present in the field of star formation is to understand how massive stars \((M > 10 M_\odot)\) form. Our present understanding of star formation is primarily based on the observations of low-mass stars. In the current paradigm (Shu et al. 1987, 1993) the formation of low-mass stars is characterized by an accretion phase, in which a central protostar and a circumstellar disk form surrounded by an infalling envelope of dust and gas, followed by a phase in which the protostar deposits linear and angular momentum and mechanical energy into its surroundings through jets and molecular outflows. Although this paradigm has been very successful in explaining what is observationally known about the formation of low-mass stars (e.g., Lada 1991), its applicability to the formation of massive stars remains arguable. In particular, alternative mechanisms such as the merging of lower mass protostars to form a massive protostar have received serious consideration lately (e.g., Bonnell et al. 1998; Portegies Zwart et al. 2001; Devine et al. 1999). There is, however, no known unquestionable case of a circumstellar disk associated with a massive O-type protostar. The search for disks around independent high-mass protostars is inherently difficult. The photoevaporation timescale of disks by the radiation from the central star (Yorke & Welz 1996; Hollenbach 1997) can be relatively short, and disks may be destroyed before the dispersal of the molecular cloud core. If other OB stars in the region have been formed before, the object studied may be embedded in bright free-free emission that will make the search difficult for the relatively weak millimeter emission from the disk.

We report here 7 mm continuum observations made with the Very Large Array (VLA) toward three luminous \((L \geq 6 \times 10^4 L_\odot)\) objects, selected from the sample of high-mass protostellar candidates of Sridharan et al. (2002), that are associated with powerful bipolar CO outflows (indicating the presence of a collimated outflow and thus suggesting the presence of a disk). The main goal of these observations was to search for either circumstellar disks or hypercompact regions of ionized gas around O-type protostars.

2. OBSERVATIONS

The observations were made with the VLA of the National Radio Astronomy Observatory\(^1\) on 2003 April 25. Each source was observed for 45 minutes, under good weather conditions, in the Q(7 mm) band using the standard VLA continuum mode (four

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IFs, 50 MHz per IF). To minimize the effect of atmospheric phase noise, we observed in the fast-switching mode with a cycle of 120 s. The data were edited and calibrated by applying the complex gain solution from the calibration source following the standard VLA procedures. The flux density scale was determined by observing the source 3C 286, for which we assumed flux densities of 1.45 Jy at 7 mm. In order to correct the amplitude and phase of the interferometer data for atmospheric and instrumental effects, we observed, before and after every on-source scan, the calibrator J1851+005. Standard calibration and data reduction were performed using AIPS. Maps were made by Fourier transformation of the interferometer data using the AIPS task imagr. The noise level in the images was in the range 0.12–0.16 mJy beam\(^{-1}\). The array was in the D configuration, resulting in a synthesized beam of \( \sim 2''\) at 43.4 GHz. In this observing session the source IRAS 18566+0408 was also observed, revealing that its 7 mm emission probably arises from dust. This source is discussed in detail in Araya et al. (2007).

We also made use of the archival VLA radio-continuum data and found that all three regions have been previously observed at centimeter wavelengths. A summary of the archive data used here is given in Table 1.

### 3. RESULTS AND DISCUSSION

We detected 7 mm continuum emission toward each of the three observed sources. The position, flux densities, and angular sizes of the detected radio sources are given in Table 2. In what follows we present the results of our continuum observations and discuss the nature of the detected sources in each of the regions individually. For the derivation of physical parameters we used the distances given by Sridharan et al. (2002) and listed in Table 3.

#### 3.1. IRAS 18470−0044

Figure 1 shows a contour map of the 7 mm continuum emission observed toward IRAS 18470−0044. The emission arises from two distinct compact sources separated by 28\(^{\prime\prime}\) (labeled A and B). Both sources were also detected at 3.6 and 6.0 cm wavelengths. A contour map of the 3.6 cm emission is shown in Figure 1 (bottom). Component A is associated with a massive dust core detected at 850 and 450 \( \mu \)m by Williams et al. (2004) and at 1200 \( \mu \)m by Beuther et al. (2002a). At 1.2 mm the core has major and minor axes of 17\(\prime\) and 12\(\prime\), respectively, implying a core radius, estimated from the geometric mean of the axes, of 0.29 pc (assuming a distance of 8.2 kpc). The mass of the core determined from the 850 \( \mu \)m observations is 720 \( M_\odot \). The peak position of the core is marked with a cross in Figure 1.

The spectral indices of the emission between 5.0 and 43.4 GHz are \(-0.1 \pm 0.1\) and \(-0.1 \pm 0.1\) for the east (A) and west (B) components, respectively; indicating that the emission in this frequency range is optically thin thermal emission. We conclude that the emission from these two objects is free-free emission from ionized gas. Table 3 lists the distance (col. [2]) and the derived parameters of the regions of ionized gas, including diameter (col. [3]), emission measure (col. [4]), and electron density (col. [5]), the minimum number of ionizing photons required to maintain the ionization of the nebula (col. [6]), and inferred spectral type of the exciting star (col. [7]). They were calculated following the formulation of Mezger & Henderson (1967), assuming that the gas has constant electron density and an electron temperature of 10\(^4\) K.

The regions of ionized gas have radii of 0.021 and 0.029 pc, in the range of those of ultracompact (UC) \( \mathrm{H II} \) regions, and densities of 4.3 \( \times \) 10\(^3\) and 2.5 \( \times \) 10\(^3\) \( \mathrm{cm}^{-3} \), much lower than those of UC \( \mathrm{H II} \) regions. We suggest that these small regions of ionized gas are deeply embedded within molecular cloud cores with high densities and large turbulent motions, and have already reached pressure equilibrium with the dense ambient gas (e.g., De Pree et al. 1995; Xie et al. 1996). The equilibrium radius is given by (see Garay & Lizano 1999)

\[
R_e = 0.034 \left( \frac{N_a}{3 \times 10^{48} \text{ s}^{-1}} \right)^{1/3} \left( \frac{4 \times 10^5 \text{ cm}^{-3}}{n_o} \right)^{2/3} \times \left( \frac{T_e}{10^4 \text{ K}} \right)^{2/3} \left( \frac{3 \text{ km s}^{-1}}{\Delta v} \right)^{4/3} \text{ pc},
\]

where \( n_o \) is the density of the ambient gas, \( N_a \) is the rate of ionizing photons emitted by the exciting star, and \( \Delta v \) is the line width of the molecular emission from the ambient gas. The time to reach pressure equilibrium is

\[
t_{eq} = 4.8 \times 10^3 \left( \frac{N_a}{3 \times 10^{48} \text{ s}^{-1}} \right)^{1/3} \left( \frac{4 \times 10^5 \text{ cm}^{-3}}{n_o} \right)^{2/3} \times \left( \frac{T_e}{10^4 \text{ K}} \right)^{2/3} \left( \frac{3 \text{ km s}^{-1}}{\Delta v} \right)^{7/3} \text{ yr}.
\]
Component A is projected right at the center of the massive and dense core, which has an average molecular gas density of $1.4 \times 10^5$ cm$^{-3}$ and a line width in optically thin molecular transitions of 2.8 km s$^{-1}$ (Beuther et al. 2002a). Using these values and the total number of ionizing photons per second needed to excite this component, $2.1 \times 10^{46}$ s$^{-1}$, we find that the equilibrium radius is $\sim 0.014$ pc, in good agreement with the observed radius of 0.021 pc. The time to reach pressure equilibrium is $\sim 2 \times 10^3$ yr. The actual age of the IRAS 18470–0044 massive-star-forming region may be much larger than this value and thus might not correspond to an object in a very early stage of evolution.

The total far-infrared luminosity of the IRAS 18470–0044 source, whose angular extent encompasses both regions of ionized gas, is $7.9 \times 10^4 L_\odot$ (Sridharan et al. 2002). On the other hand, the total luminosity of the ionizing sources is $2.3 \times 10^4 L_\odot$. The difference in the inferred luminosities from the radio and FIR observations is most likely due to the presence of a group of non-ionizing stars that account for a fraction of the total bolometric luminosity but produce a negligible amount of ionizing photons. This explanation is strongly supported by our analysis of unpublished archival Spitzer Space Telescope IRAC observations, which show the presence of several embedded sources within the angular extent of the IRAS source. However, it should be noted that the presence of dust-absorbing ionizing stellar UV photons is most probably also contributing to the difference in the luminosities inferred from the radio and the FIR observations.

### 3.2. IRAS 19217+1651

IRAS 19217+1651 is associated with a massive dust core detected at 850 and 450 $\mu$m by Williams et al. (2004) and at 1200 $\mu$m by Beuther et al. (2002a). At 1.2 mm the core has major and minor axes of 18" and 15", respectively, implying a core radius, estimated from the geometric mean of the axes, of 0.42 pc (assuming a distance of 10.5 kpc). The mass of the core determined from the 850 $\mu$m observations is $2 \times 10^3 M_\odot$. Beuther et al. (2002b) detected class II methanol and water masers near the peak position of the dust core, suggesting that this is a massive-star-forming region in an early stage of evolution.

Figure 2 (top) shows a contour map of the 7 mm continuum emission observed with the VLA toward IRAS 19217+1651. Most of the emission arises from a single bright source, although there is evidence of a weaker component to the north. VLA observations at centimeter wavelengths (X, U, and K bands) show that emission arises from two components. This is illustrated in Figure 2 (bottom), which presents a contour map of the emission observed at 22.5 GHz, showing that the emission arises from a bright compact component (labeled A), with an angular size of $\sim 0.16''$, and a more extended, weaker component (labeled B) located $\sim 1''$ northeast of component A, with an angular size of 0.8". The peak of the 7 mm source coincides with component A. The

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### TABLE 3

| Source                  | $D$ (kpc) | Diameter (pc) | Emission Measure ($n_e$) | $n_e$ (cm$^{-3}$) | $N_i$ (s$^{-1}$) | Spectral Type |
|-------------------------|-----------|---------------|--------------------------|------------------|-----------------|---------------|
| 18470–0044A             | 8.2       | 0.042         | 1.1 x 10$^6$             | 4.3 x 10$^3$     | 2.1 x 10$^{46}$ | B0.5          |
| 18470–0044B             | 8.2       | 0.057         | 5.3 x 10$^5$             | 2.5 x 10$^3$     | 1.5 x 10$^{46}$ | B0.5          |
| 19217+1651A             | 10.5      | 0.099         | 7.0 x 10$^4$             | 2.5 x 10$^3$     | 5.5 x 10$^{47}$ | O9.5          |
| 19217+1651B             | 10.5      | 0.041         | 4.3 x 10$^6$             | 8.4 x 10$^3$     | 6.3 x 10$^{46}$ | B0            |
| 23151+5912              | 5.7       | 0.0006°*      | 2.3 x 10$^9$             | 1.7 x 10$^6$     | 6.2 x 10$^{45}$ | B0.5          |

* The size of this source is estimated from the fit to its spectrum and not from an observed size.
The radio-continuum spectrum of component A, in the range from 8.4 to 43.4 GHz, is shown in Figure 3 (top). The spectrum is reasonably well modeled (dotted line) by a homogeneous region of ionized gas with an emission measure of $7.0 \times 10^{6}$ pc cm$^{-6}$ and an angular size of 0.19$''$. The region of ionized gas is optically thick below 15 GHz. The total number of ionizing photons per second required to excite this region is $5.9 \times 10^{46}$ s$^{-1}$, which could be supplied by an O9.5 ZAMS star. The direct interpretation of these data is that, since the total number of ionizing photons per second required to excite this region is $6.9 \times 10^{46}$ s$^{-1}$, we are observing an independent H II region ionized by a B0.5 ZAMS star with a luminosity of $2.0 \times 10^{4} L_{\odot}$. However, the high angular resolution images (see the 22.5 GHz image in Fig. 2) suggest that component B could be ionized gas outflowing from component A. Is this alternative possible? The angular separation between components A and B is $\sim 1''$, which at a distance of 10.5 kpc gives a physical distance of $1.6 \times 10^{17}$ cm. Moving at a velocity of 10 km s$^{-1}$, the ionized gas will take about 5000 yr to move from component A to component B. On the other hand, since component B has a deconvolved angular diameter of 0.8$''$, we estimate for this source an average electron density of $8.9 \times 10^{3}$ cm$^{-3}$ and a recombination timescale of only 14 yr. We then conclude that component B requires its own ionizing star.

3.3. **IRAS 23151+5912**

IRAS 23151+5912 is associated with a massive dust core detected at 850 and 450 $\mu$m by Williams et al. (2004) and at 1200 $\mu$m by Beuther et al. (2002a). At 1.2 mm the core has major and minor axes of 16.5$''$ and 14.4$''$, respectively, implying a core radius of 0.21 pc (assuming a distance of 5.7 kpc). The mass of the core...
determined from the 850 μm observations is $3 \times 10^2 \, M_\odot$. Water masers were detected near the peak position of the core by Beuther et al. (2002b).

The 7 mm continuum observations toward IRAS 23151+5912 show the presence of a single source, as illustrated in Figure 4 (top). We also detected emission from this source at 3.6 cm (with a total flux density of 0.27 ± 0.04 mJy), as shown in Figure 4 (bottom). The radio-continuum spectrum, shown in Figure 3 (bottom), can be well fitted by that of a uniform-density region of ionized gas with an emission measure of $2.3 \times 10^9 \, \text{pc} \, \text{cm}^{-6}$ and an angular size of $0.02''$ (or $6 \times 10^{-4} \, \text{pc}$). The high emission measure and small size of this H II region are characteristic of hypercompact H II regions (Kurtz 2000; Hoare et al. 2007). Unfortunately, the modest angular resolution of our data does not allow a direct measurement of the angular size of this source, and only an upper limit is possible (see Table 2). Additional observations of very high angular resolution are needed to test the nature of this source as a hypercompact H II region. Hypercompact H II regions are thought to mark the earliest stages of evolution of regions of ionized gas, being formed in the accretion phase of hot molecular cores (Keto 2002, 2003; González-Avilés et al. 2005; Avalos et al. 2006). We conclude that IRAS 23151+5912 is indeed associated with a massive-star-forming region in a very early stage of evolution. We note that the spectral index of the 7 mm source between 8.4 and 43.4 GHz is $1.1/1.04$. This value is typical of the spectral index of hypercompact H II regions at centimeter wavelengths, which suggests the presence of non-uniform-density gas. With the presently available data we cannot, however, discern whether or not the ionized gas exhibits density gradients. In particular, we cannot rule out the possibility that the source is an ionized stellar wind.

The rate of ionizing photons needed to excite the H II region is $5.5 \times 10^{45} \, \text{s}^{-1}$, which could be supplied by a B0.5 ZAMS star with a luminosity of $1.1 \times 10^4 \, L_\odot$. The FIR luminosity of the region inferred from the IRAS observations is, however, $1.0 \times 10^5 \, L_\odot$ (Sridharan et al. 2002). The most likely explanation for the discrepancy in the luminosities inferred from the radio and FIR observations is that, due to the coarse angular resolution of the IRAS observations, the FIR luminosity includes the contribution of the star or stars ionizing the large cometary H II region located 30'' northwest of the dense core (see Fig. 5). This cometary H II region has a flux density of $\sim 20 \, \text{mJy}$, which requires a B0.5 ZAMS star with a luminosity of $2.0 \times 10^4 \, L_\odot$ to maintain its ionization. Another contributing effect could be absorption of UV photons by dust within the hypercompact H II region. There are no archival Spitzer data for this source.

4. SUMMARY

We made 7 mm high angular resolution continuum observations, using the VLA, toward three regions of massive-star formation thought to be in early stages of evolution. These regions are associated with energetic molecular outflows, and two of them
were not previously detected in radio-continuum observations with the VLA. The main objective was to search for the presence of disks and/or hypercompact regions of ionized gas. Our main results and conclusions are as follows.

Emission at 7 mm was detected toward the three regions. Toward IRAS 18470−0044 we detected two objects with spectral indices between 4.8 and 43.4 GHz of ~0.1, indicating that the emission is free-free radiation arising from optically thin H ii regions excited by stars with spectral type B0.5. We conclude that these small H ii regions are embedded within massive and dense cores and have already reached pressure equilibrium with their dense and turbulent molecular surroundings.

In the case of IRAS 19217+1651 we detected two components: component A is a hypercompact H ii region that is optically thick below 15 GHz, while component B is optically thin in the 8.4–22.5 GHz range. We discuss whether component B could be ionized gas outflowing from component A but conclude that each component has its own ionizing star.

Toward IRAS 23151+5912 we detected a hypercompact H ii region that can be modeled as a source with a radius of 3 \times 10^{-4} pc (or 57 AU) and an emission measure of 2.3 \times 10^9 pc cm^{-6}. We conclude that IRAS 23151+5912 is indeed a massive-star-forming region in a very early stage of evolution, with the hypercompact H ii region being formed while the suspected hot molecular core around it is still probably undergoing accretion.

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