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EXPANDED VERY LARGE ARRAY CONTINUUM OBSERVATIONS TOWARD HOT MOLECULAR CORE CANDIDATES

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ABSTRACT

We have used the Expanded Very Large Array (EVLA) with two 1 GHz wide bands to obtain *K*-band (1.3 cm) continuum observations toward the following five hot molecular core candidates: IRAS 18151 − 1208, IRAS 18182 − 1433, IRAS 18345 − 0641, IRAS 18470 − 0044, and IRAS 19012 + 0536. The sources were selected from the 2002 list of Sridharan et al. and are characterized by high FIR luminosity, dense molecular and dust condensations, massive large-scale CO flows, and the absence of strong cm continuum emission. These properties are indicative of massive star-forming regions in an evolutionary phase prior to ultra- or hypercompact H ii regions. We detect a total of 10 individual 1.3 cm continuum sources toward this sample, and derive in-band spectral indices between 19.3 and 25.5 GHz consistent with thermal free–free emission, for all sources except component A in IRAS 18182 − 1433, which has a negative spectral index indicative of synchrotron emission. We suggest that in most cases the 1.3 cm sources are due to shock-induced ionization, rather than direct photoionization by massive objects. The momentum rate present in these ionized flows is sufficient to drive the large-scale molecular flows. We discuss a number of morphological features supporting this hypothesis. The present observations demonstrate that the EVLA has sufficient sensitivity to study the regions near very young massive stars in the cm continuum.

Key words: ISM: jets and outflows – radio continuum: stars – stars: formation

1. INTRODUCTION

Radio continuum observations have always played a major role in the study of massive star formation.Unaffected by interstellar extinction, studies like, e.g., Mezger & Henderson (1967) were able to identify H ii regions on a Galactic scale, and these authors correctly interpreted their continuum radiation as free–free emission from ionized gas in compact H ii regions, i.e., remnants of the recent birth process of a massive star, now responsible for ionizing the regions. The development of radio interferometry enabled another milestone in the quest to understand the formation of massive stars to be passed. The arcsecond beam resolution of the Very Large Array (VLA) and mJy sensitivity allowed the identification and Galaxy-wide studies of ultracompact (UC; e.g., Wood & Churchwell 1989) and hypercompact (HC; e.g., Kurtz 2005) H ii regions, which have typical sizes of 0.1 pc (UC) and 0.01 pc (HC), and electron densities of about 10^4 cm^{-3} (UC) and 10^6 cm^{-3} (HC). Due to their small size and high electron densities UC and HC H ii regions are thought to be the youngest observable H ii regions.

At earlier evolutionary stages when the newly formed (or forming) massive stars have not yet ionized much of their surrounding matter, sites of massive star formation appear as compact condensations of dense ($n_{\mathrm{H}_2} \geqslant 10^7$ cm^{-3}) and hot ($T \geqslant 200$ K) molecular gas, which are bright in high excitation lines (e.g., CH_3CN(12–11); Beltrán et al. 2005; Araya et al. 2005). These regions are called hot, dense molecular cores (Zinnecker & Yorke 2007) or simply hot molecular cores (HMC; Cesaroni et al. 2010; Cesaroni 2005) after their most prominent example in Orion (e.g., Loren & Mundy 1984). The presence of a substantial amount of hot molecular gas on a small scale requires a central heating source (Kaufman et al. 1998), i.e., a massive star or protostar.

While the free–free emission from photoionized gas in UC and HC H ii regions is relatively bright, this earlier evolutionary HMC stage is essentially thought to be radio quiet. However, there are a number of processes which can result in detectable radio continuum emission from a massive central object. Among these are accretion shocks (e.g., Neufeld & Hollenbach 1994, 1996), thermal and non-thermal jets (e.g., Anglada 1996; Hofner et al. 2007; Reid et al. 1995), H^- free–free emission (e.g., Reid et al. 2007), photoionization of accretion disks (Hollenbach et al. 1994), and stellar winds (e.g., Gibb & Hoare 2007). At distances of a few kpc, these processes are expected to result in sub-mJy flux densities, which should be detectable with the improved continuum sensitivity of the expanded VLA (hereafter EVLA). We are carrying out a survey toward a sample of massive objects in evolutionary stages prior to UC/HC ii regions with the goal of studying these weak emission processes. In this Letter we report results of pilot observations toward five HMC candidates.

The observed sources were selected from the sample of Sridharan et al. (2002). All have *IRAS* luminosities above 10^4 $L_\odot$ and were reported as non-detections in the 3.6 cm VLA snapshot observations of Sridharan et al. (2002).[8] All of the sources contain massive, compact dust cores (Beuther et al. 2002a) and drive massive molecular flows (Beuther et al. 2002b). Based on these observational properties these regions were interpreted as containing massive stars in an evolutionary phase prior to that of UC/HC ii regions. An inspection of the CORNISH

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[8] The reported flux density of 27 mJy for IRAS 18345 − 0641 arises from an unrelated source about 3′ toward the southeast.

database (Purcell et al. 2008) results in non-detections at 6 cm for all sources, except for IRAS 18151 − 1208, which was not observed in the CORNISH survey. Typical upper limits at both wavelengths are about 1 mJy beam^{-1}.

2. OBSERVATIONS AND DATA REDUCTION

We observed the five candidate HMCs listed in Table 1 from the list of Sridharan et al. (2002). The observations were carried out on 2010 November 11 and 14 with the EVLA in the C-configuration within the EVLA RSRO program AH1011 (10B-124). We configured the WIDAR correlator using two intermediate frequencies (IFs) centered at frequencies of 19.512 and 25.488 GHz, respectively. Each IF had a bandwidth of 1024 MHz comprised of eight 128 MHz spectral windows with 64 channels each, i.e., 512 channels per IF.

On both days we observed J1733−1304 as a bandpass calibrator. Flux calibration is based on observations of 3C48 for IRAS 18470 − 0044 and IRAS 19012 + 0536 (November 11), and 3C286 for IRAS 18151 − 1208, IRAS 18182 − 1433, IRAS 18345 − 0641 (November 14). Observations of our targets were alternated with observations of J1851+0035 (November 11) and J1832−1035 (November 14) with a cycle time of 5 minutes to calibrate the complex gain. Interferometric pointing observations of the calibrator sources were obtained hourly using the X-band (3.6 cm) receivers and corrections were applied online.

Data reduction was done with the CASA software provided by NRAO. Initial inspection of the data showed strong radio frequency (RF) interference between 19.640 and 20.024 GHz, which rendered 384 MHz of the lower frequency IF unusable. After initial flagging, we first carried out a bandpass calibration based on observations of J1733−1304. Phase and amplitude corrections were derived from observations of the complex gain calibrators and applied to the data. The UV data of each IF were separately inverted and cleaned using CASA task *clean*, neglecting the frequency dependence in gridding the UV data. In Figure 1 we show the images of the upper IF (25.5 GHz) data; the images of the lower IF are similar.

3. RESULTS

We detect a total of 10 individual sources in the 5 targets. We label the continuum components in each source with capital letters from east to west. In Table 2 we list the basic observational parameters derived from the 25.5 GHz maps. In Column 1 we list the source name, in Columns 2 and 3 the peak positions, and in Column 4 the peak intensity. Column 5 lists the corresponding brightness temperature. In Column 6 we list the total 25.5 GHz flux density integrated over the source, and in Column 7 the deconvolved size of the emitting region. Column 8 contains the spectral index α between 19.3 and 25.5 GHz. To calculate the latter we first convolved the 25.5 GHz maps with the beam of the 19.3 GHz map and obtained the value for α at the position of peak intensity. Assuming a 5% uncertainty in the peak intensities the error in the spectral index is about 0.3. Most of the sources reported here are new detections and demonstrate that with the improved sensitivity of the EVLA the dense, dusty molecular cores where massive stars form can be explored in the radio continuum. Below we comment in more detail on each source.

3.1. IRAS 18151−1208

This region consists of three dust cores (Beuther et al. 2002a); we have observed the central component, mm1. Recent Submillimeter Array (SMA) observations (Fallscheer et al. 2011) report a northeast–southwest elongated 1.3 mm continuum structure, which is perpendicular to the direction of a highly collimated flow seen in CO(2–1) as well as in H_2 jets (Davis et al. 2004). Continuum components A and B are coincident with the dust structure. Their compact nature and spectral index are consistent with those expected in ionized jets, so that a relation to the outflow is likely.

Fallscheer et al. (2011) also report a second highly collimated flow, centered about 15″ toward the east of components A and B. Our data show a marginal detection at this position, which likely marks the position of the driving object. However, due to the relatively low level of detection we will not discuss this source in this Letter.

3.2. IRAS 18182−1433

As above, our cm continuum sources are coincident with a dense dust core observed with the SMA (Beuther et al. 2006). Multiple outflows are thought to arise from the dust core. Zapata et al. (2006) reported VLA C-array observations at 3.6, 1.3, and 0.7 cm toward IRAS 18182 − 1433[9] and reported detections of components A and B. Component B is clearly elongated in the southeast–northwest direction, and a highly collimated CO flow is seen in the same direction. We propose that component B is an ionized jet which drives this flow. Also, component A is located along the flow axis. The negative spectral index of this source suggests a shock origin within the flow (see also Zapata et al. 2006).

3.3. IRAS 18345−0641

We detect a compact source coincident with the 1.3 mm dust core mapped by Beuther et al. (2002a). Component A is unresolved and has a spectral index of 0.6. No interferometric data exist toward this region, but Beuther et al. (2002b) report a massive flow observed in CO(2–1). The flow center is located near the dust core, and we propose that continuum component A is an ionized jet at the base of the flow.

3.4. IRAS 18470−0044

The characteristics of this source are similar to those of IRAS 18345−0641. Single dish observations show a single massive dust core, associated with a massive CO flow in the east–west direction. Deep VLA D-array observations were carried out at 0.7 cm by Garay et al. (2007) which detected components B and C at this wavelength.[10] We detect three continuum sources within the core. Component A is a new detection. Components B and C are clearly extended and have slightly negative spectral indices, which within errors are consistent with optically thin free–free emission from ionized gas. Garay et al. (2007) suggest that these objects are H II regions in pressure equilibrium with the surrounding molecular gas.

3.5. IRAS 19012+0536

Similar to the above this source shows a dense dust core associated with a massive molecular flow (Beuther et al. 2002a,

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[9] Note the different nomenclature in Zapata et al. (2006).

[10] Note the different nomenclature in Garay et al. (2007).

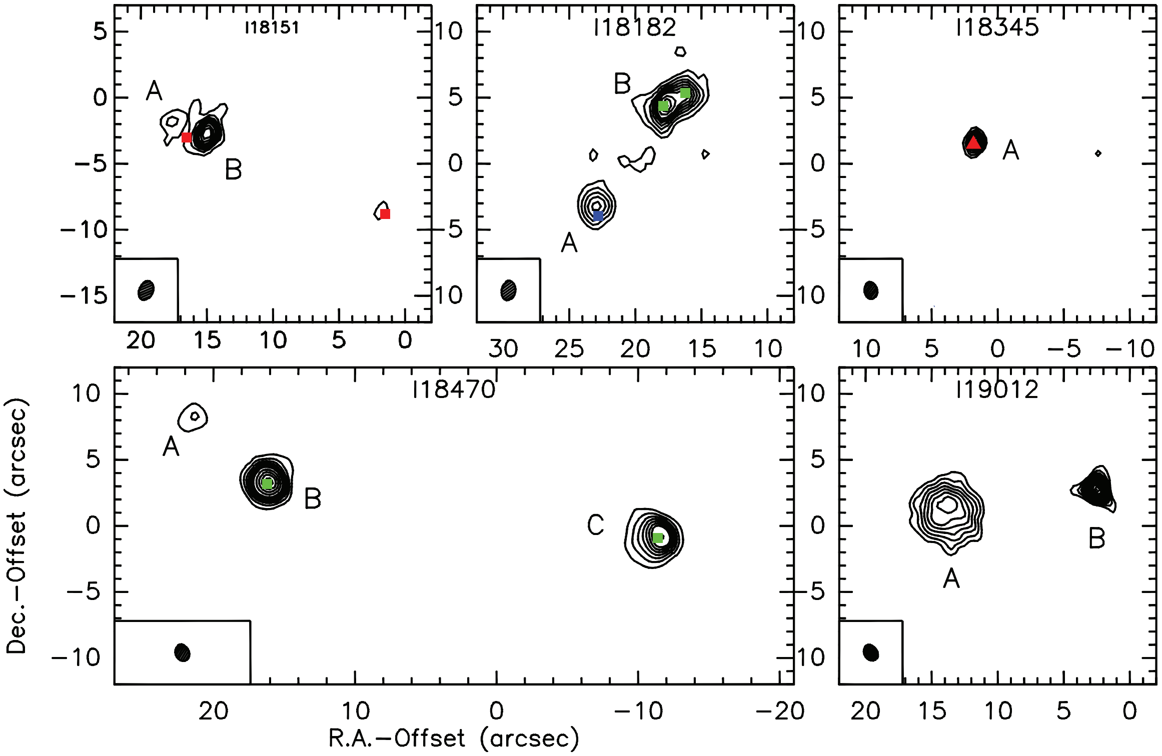

Figure 1. 25.5 GHz maps toward the five HMC candidate sources observed with the EVLA in the C-configuration. Contours are in units of map rms, with levels ranging from 3 to 15 with steps of 2σ, and 20 to 60 in steps of 5σ. Coordinates are offset from the *IRAS* position listed in Sridharan et al. (2002). The green squares mark the position of previous detections at 7 mm (Garay et al. 2007; Zapata et al. 2006), the blue square at 1.3 cm (Zapata et al. 2006). The red squares in IRAS 18151−1208 mark the positions of the 1.3 mm cores (Fallscheer et al. 2011), and the red triangle in IRAS 18345−0641 the position of 6.7 GHz CH_3OH masers (Bartkiewicz et al. 2009).

Table 1
Observed Sources

Source	R.A. (J2000)	Decl. (J2000)	d^a (kpc)	rms (μJy beam^{-1})	θ_{FWHM} ($'' \times ''$, °)
IRAS 18151−1208	18:17:57.1	−12:07:22	3.0	16	1.52 × 1.05, −22.7
IRAS 18182−1433	18:21:07.9	−14:31:53	4.5^b	13	1.50 × 1.05, −09.4
IRAS 18345−0641	18:37:16.8	−06:38:32	9.5	10	1.32 × 0.98, +09.1
IRAS 18470−0044	18:49:36.7	−00:41:05	8.2	25	1.29 × 0.97, +16.1
IRAS 19012+0536	19:03:45.1	+05:40:40	4.6^b	14	1.29 × 0.99, +32.5

Notes.
[a] Distances from Sridharan et al. (2002).
[b] Near kinematic distance.

Table 2
25.5 GHz Continuum Parameters

Source	R.A. (J2000)	Decl. (J2000)	$I_\nu{}^a$ (μJy beam^{-1})	$T_b{}^b$ (K)	S_ν (μJy)	$\theta_a \times \theta_b$ ($'' \times ''$)	α (19.3–25.5 GHz)
IRAS 18151−1208 A	18:17:58.30	−12:07:23.6	99	0.1	260	1.7 × 1.6	1.2
B	18:17:58.11	−12:07:24.8	515	0.6	710	0.8 × 0.6	0.8
IRAS 18182−1433 A	18:21:09.47	−14:31:56.2	187	0.2	570	1.9 × 1.7	−0.9
B	18:21:09.11	−14:31:48.6	488	0.6	1520	3.1 × 1.4	1.5
IRAS 18345−0641 A	18:37:16.91	−06:38:30.4	174	0.3	210	0.8× $\leqslant$ 0.6	0.6
IRAS 18470−0044 A	18:49:38.12	−00:40:56.8	168	0.3	660	2.2 × 1.7	−0.4
B	18:49:37.77	−00:41:01.8	1185	1.8	3590	1.6 × 1.6	−0.3
C	18:49:35.92	−00:41:05.8	644	1.0	2920	2.3 × 2.1	−0.4
IRAS 19012+0536 A	19:03:46.02	+05:40:41.8	255	0.4	2690	3.5 × 3.4	0.0
B	19:03:45.27	+05:40:42.8	687	1.0	810	$\leqslant$ 0.6	0.1

Notes.
[a] Peak brightness within synthesized beam listed in Table 1.
[b] Peak brightness temperature.

2002b). We detect two radio continuum sources associated with this core. Component A is a low surface brightness, extended region with flat spectral index, whereas component B is unresolved with also a flat spectral index.

4. DISCUSSION

Our EVLA observations detect 1.3 cm continuum emission in all five of the massive star-forming regions that we observed. With the exception of IRAS 18345 − 0641, the regions show multiple sources, generally consistent with thermal free–free emission. The only exception to the latter is the source IRAS 18182 − 1433 A which has a negative spectral index, thought to arise from synchrotron emission related to shocks (e.g., Zapata et al. 2006). The low peak brightness temperatures indicate at least for the sources with rising spectral index that an unresolved component must exist within these sources. As mentioned above all of the sources have massive, large-scale molecular flows (Beuther et al. 2002b). If one computes the energy requirement assuming optically thin emission from photoionized H II regions one finds that the resulting luminosities fall short from the FIR luminosities measured by *IRAS* by up to one order of magnitude. While this could be due to absorption of ionizing photons by dust within the ionized gas, as well as to contribution from other FIR sources in the large *IRAS* beam, another possibility is that the 1.3 cm sources are manifestations of the energetic flows driven by the massive protostars rather than gas photoionized by a massive star. In this case the ionization is likely shock induced, i.e., UV radiation from hot, shocked regions ionizes the surrounding medium (e.g., Curiel et al. 1989). Using the relation presented by Anglada (1996, see his Figure 4) one can estimate the momentum rate $\dot{p}$ provided by the ionized flows from the quantity $S_\nu\, d^2$. The predicted values for $\dot{p}$ range between 8×10^{-3} and $1.3\ M_\odot\ \mathrm{yr}^{-1}\ \mathrm{km\ s}^{-1}$, in all cases exceeding the values for $\dot{p}$ measured by Beuther et al. (2002b) for the large-scale CO flows. Thus, there appears to be sufficient force in the ionizing flows to drive the observed molecular flows.

For two of our sources (IRAS 18151 − 1208, IRAS 18182 − 1433) interferometric observations show that the continuum sources are clearly associated with the flows from the region. Further support for the above hypothesis comes from a comparison of our radio data with *Spitzer*/GLIMPSE data: IRAS 18182−1433 component B and IRAS 19012 + 0536 component B are coincident with "green fuzzies," indicative of shocked gas as expected from regions where outflowing gas interacts with the surrounding medium (e.g., De Buizer & Vacca 2010). For IRAS 18470 − 0044, Garay et al. (2007) interpreted our components B and C as HC H II regions. While this interpretation is consistent with our data, we point out that the three regions are aligned in the direction of the large-scale CO flow (Beuther et al. 2002b). Furthermore, component C shows a cometary morphology along that same direction similar to what is seen, for instance, in IRAS 20126 + 4104 component N2 (Hofner et al. 2007), thus shock-induced ionization might be an alternative explanation for the sources in IRAS 18470 − 0044.

5. SUMMARY

We have carried out 1.3 cm pilot observations for a future large EVLA continuum survey toward massive protostars. Our observations demonstrate the excellent continuum sensitivity of the EVLA which resulted in detection of all observed sources, which were previously mostly undetected in the radio continuum. For most of the sources observed, the radio continuum emission is consistent with free–free emission from thermal jets, hinting that the large-scale CO flows which appear to be ubiquitous toward these HMC candidates are driven by ionized jets. Only a handful of such jets have been found so far (e.g., Guzmán et al. 2010), and our observations demonstrate that the EVLA will be able to make a major contribution to the study of these objects. This, and the exploration of additional possible radio continuum processes, is the subject of a future sub-arcsecond resolution, and multi-band survey toward massive protostars.

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