An Imaging Survey of Submillimeter Dust Emission in Massive Star Forming Regions

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Abstract We present some preliminary results of an 870 μm continuum imaging survey of a sample of 76 massive star forming regions. Strong submillimeter dust emission is detected in almost all sources associated with 6.7 GHz methanol masers. The absence of dust emission in only three exceptions may be interpreted by different maser pumping mechanism(s). Five morphology types of emission distributions are classified. About 130 submillimeter sources are detected in 76 regions, among which 17 sources are found to be hot core candidates and about 40 are promising for Class—0 candidates. Some interesting sources were also mapped in the CO(3—2) and outflow activities are found to be quite common in massive star forming regions.

1 Introduction

In recent years the formation of massive stars ($M \geq 8\ M_\odot$) has received growing attention, because of their important role in galactic evolution and the recognition that the majority of low-mass stars are formed together with high-mass stars in clusters (Clarke et al. 2000). At present, however, the formation and early evolution of massive stars still remains a major puzzle, not only due to the large distances of massive star forming sites, but also due to their clustered appearance which makes it very hard to isolate individual young massive objects.

Hot molecular cores are thought to be the precursors of UC HIIs, and therefore the formation sites of the massive stars. Being related to the formation of massive stars, 6.7 GHz methanol masers provide ideal sites to probe the earliest stages of massive stellar evolution (e.g. Menten 1992). At present, about 400 IRAS sources are known to be associated with 6.7 GHz methanol masers (MacLeod et al., 1998; Slysh et al., 1999; Szymczak et al., 2000 and references therein). We can use these masers as a beacon searching for hot cores. Since 1998, we have been searching for new hot cores from a catalog of massive young objects (Chan et al. 1996) in which many are 6.7 GHz methanol masers. New hot core candidates were identified, based on the presence of high velocity molecular CO emission and high rotational temperatures derived from NH_3 metastable inversion lines (Mao 1999; Mao et al. 2002).

Submillimeter dust emission is a good tracer of column density in star forming regions as it is mostly optically thin. Dust temperatures, column densities and masses can be easily estimated from observed fluxes. Hatchell et al. (2000) found that sources with hot cores can be identified much faster from submillimeter imaging than from spectral line observations. Previously identified hot core sources show more strongly centrally peaked emission. Therefore, submillimeter continuum imaging of molecular cloud is the most efficient way to pick up hot cores.

In this contribution, we present some preliminary results of an 870 μm dust continuum imaging survey towards a sample of massive star forming regions.

2 Samples and Observations

To select the sample, we combine the massive YSO catalog from Chan et al. (1996) and the list of detected 6.7 GHz methanol masers from Szymczak et al. (2000). This results in a list of about 210 sources with $\delta > -20°$. Excluding those sources already observed at $870\,\mu$m (Walsh 2000 priv. comm.) and $1300\,\mu$m (Beuther et al. 2002), 123 objects remain as our sample. It contains 18 overlaps with the sample of Beuther et al. (2002) who selected only those sources not detected in centimeter radio continuum survey.

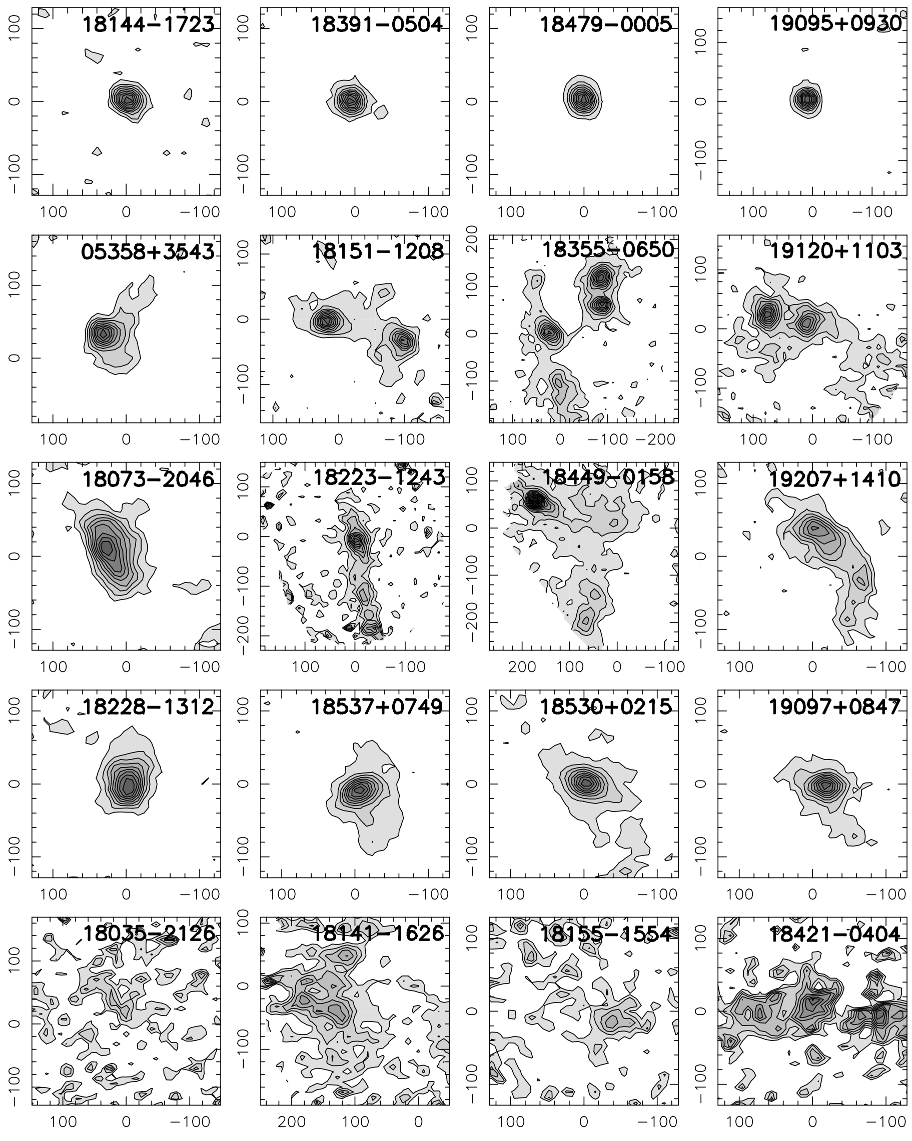

Fig. 1 HHT $870\,\mu$m continuum images of some representative morphologies (see text for details)

$870\,\mu$m dust continuum emission was imaged with the 10-m Heinrich Hertz Telescope (HHT; see Baars et al 1999) on Mt. Graham in Southern Arizona during April and May,

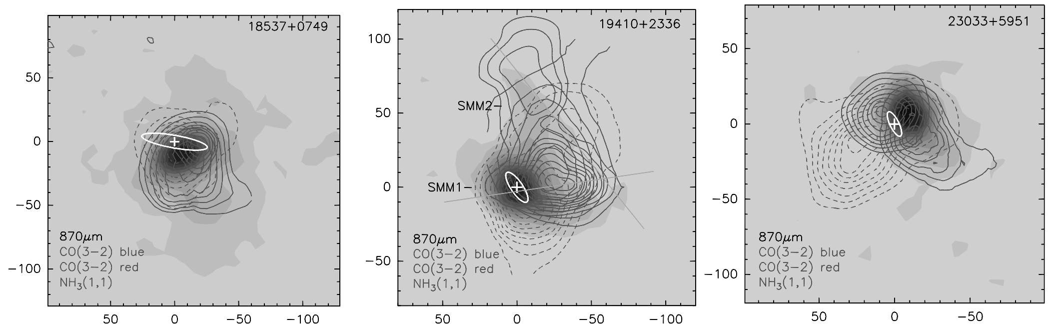

Fig. 2 CO(3–2) red- (dashed) and blue-shifted (dark solid) emission , NH_3(1,1) total integrated intensity contours (light solid) overlaid on 870 μm continuum (grey) in three selected regions.)

2000. A 19-channel bolometer array served as a backend for continuum imaging. The array covers a hexagonal 200″ field of view. The beam width of the HHT is about 22″ at 870 μm. Maps were taken using the On-The-Fly (OTF) method with a beam throw of 120″ and a scanning speed of 8″ per second. For most of the sources a single coverage (400″×300″ in size) centered at IRAS position is taken. The average r.m.s noise level is about 150 mJy in the maps. All maps were calibrated using 870 μm skydips and the standard calibrators Uranus and G 34.3+0.2, and a peak flux density of 60 Jy beam^{-1} was assumed for the latter one. At 870 μm, the typical atmospheric opacity was about 0.4 during the observations. The calibration accuracy should be better than ±20%.

3 Results

A total of 76 sources are mapped in 870 μm continuum. Fig. 1 shows some examples for five types of representative morphologies, i.e. from the 1st to the 5th row of Fig. 1 are **a)** strongly centrally peaked; **b)** multiple centrally peaked; **c)** elongated and/or filamented; **d)** a compact core with a diffused envelope surrounded and **e)** diffused or less centrally peaked, respectively. A systematic study of a complete sample of these different morphologies will help understand the formation mechanism of massive stars. Different morphologies may in fact reflect different evolution stages or even different star forming modes. While those strongly centrally peaked sources are preferable hot core candidates, those filamented regions with many fragments or multiple centrally peaked cores are very good sites for studying the clustered forming mode of massive stars. For example, most recently, about 50 fragments are revealed in a filamentary structure of the W43 main complex (Motte et al. 2002; see also IRAS 18449-0158 of Fig. 1). A detailed study on the physical conditions of these fragments suggests that they are protoclusters. The whole region is likely undergoing a Galactic mini-starburst. Those regions with diffused or less centrally peaked dust emission can hardly be the forming sites of massive stars. They are more likely undergoing a more evolved phase of massive star formation. Our main results are,

1) 130 individual sub-mm sub-sources are found in 76 regions, or 1.7 sub-sources per regions on average. Beuther et al. (2002) found a higher number 2.2 in their samples, but their 1.3 mm images were taken at a spatial resolution of 11″, two times higher than ours. As Beuther et al. (2002) have already pointed out in their paper that most of such single-dish

cores split up into a number of subcores again at even higher resolution because of their clustered forming trend of massive stars.

2) 17 sources are found to contain strongly centrally peaked submillimeter emission. We use a criteria of $F_{\rm peak}/F_{\rm total} > 0.5$, where $F_{\rm peak}$ and $F_{\rm total}$ are the peak flux and total flux, respectively. They are candidates for hot cores which are worthy of further high resolution study. About a dozen of them show a single centrally peaked simple structure. These sources can be used as candidates of calibrators for the submillimeter inteferometer like the SMA and the ALMA.

3) About 40 sources are found to be spatially not coincided with any IRAS source. These sources are most likely at earlier evolution stages than those sources with IRAS associations and therefore the promising candidates for Class 0 protostellar objects.

4) Three 6.7 GHz methanol maser sources (IRAS 18021—1950, IRAS 18141—1626, IRAS 18321— 0845) show very weak or even no detection of 870 μm continuum emission within a radius of $1'$ to the maser sites. These sources are interesting and need to be further studied. It's possible that the pumping mechanism for the 6.7 GHz methanol masers in these regions is different from generally thought radiative pumping.

We have also calculated the masses of each source. The masses of the clouds can be estimated via $M=F_\nu D^2/\kappa_\nu B_\nu(T_{\rm d})$, where F_ν is the flux density, D denotes the distance towards the cloud, $B_\nu(T_{\rm d})$ is the Plank function for temperature $T_{\rm d}$, and κ_ν is the dust opacity per unit gas and dust mass. The determination of κ_ν has been discussed in our another paper (Mao et al. 2002), and the results of these calculations will be published in a separate paper.

4 Molecular line follow-up and case studies

While we are still going on this continuum survey, some interesting regions have been selected for molecular line follow-up studies. This includes NH_3 mapping with the Effelsberg 100-m telescope, CO(3–2), CS(5–4), HCO^+(3–2) and some other molecular line emission mapping with the HHT-10m. Molecular outflows are found to be quite common in these regions. Observation details is as described in Mao et al. (2002) and a separate paper of the results is under preparation. Here we only present three examples.

4.1 IRAS 18537+0749

The cold IRAS color and the high far-infrared luminosity along with the presence of the water masers, outflows, and radio recombination lines (RRL) and the absence of UC HII regions indicate the very early stage of the ongoing massive star forming activities in this region. A total gas/dust mass of about 1200 $M_\odot$ estimated from the 870 μm continuum makes the region a promising site forming clusters. A slightly elongated centrally peaked core with a deconvolved FWHM size of about $40''$ ($\sim$0.5 pc) appears in both the 870 μm continuum and the CS(5–4) line emission, indicative of a disk-like envelope and/or the existence of multiple cores. Strong red wings extending to $\sim$50 km s^{-1} are detected in CO(3–2). The bulk of the blue-shifted emission is, however, hidden in the CO emission due to a strong self-absorption that is most likely from the foreground cloud(s). An outflowing gas mass of about 15 $M_\odot$ is estimated from our CO(3–2) observations.

4.2 IRAS 19410+2336

This source has, to our knowledge, not been studied in detail before. It has not been found in the 5 GHz VLA survey by Becker et al.(1994). Our CO map of this region shows some interesting outflow structures. While a prominent pair of lobs (red and blue) centered close to the IRAS point source as well as the main peak of 870 μm continuum map, we found there is another outflow to the north with two lobs located at either side of a weaker continuum peak. Two straight lines in middle panel of Fig. 2 imply the possible axis for two outflows. Missed in the IRAS survey, the later one may trace a much younger star formation. Relative narrow NH_3 line width may also indicate the cooler gas and thus an early star forming phase of this source.

4.3 IRAS 23033+5951

This source has not been found in the 5 GHz VLA survey by Becker et al.(1994), but detected in 6.7GHz CH_3OH maser. We have mapped this region in CO(3-2) and NH_3 (1,1), (2,2) line as well. An outflow is clearly shown, but centered somewhat away from IRAS source. NH_3 core appearance resembles very much that of 870 μm continuum core, indicating the tight relation between gas and dust in this region. We suppose this source to be in a phase before a HII region evolved to be visible, and therefore a good candidate protostar.

5 Future works

Firstly, we need to finish the survey to have a comprehensive statistics. Since our samples are mostly 6.7 GHz methanol masers, after such a survey we can study the correlations between maser luminousities and core masses, dust temperatures. Secondly, to identify the hot cores, molecular line observations are needed. So as a follow-up program, we will concentrate on those hot core candidates only for line observations of selected molecules like CH_3CN, CH_3OH, HNCO and HCO^+ etc.. Finally, to eventually dig out the hot cores, high resolution line and continuum observations are crucial.

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