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LETTERS

Molecular Cores in Different Evolutionary Stages near Luminous IRAS Sources and UC HII Regions *

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Abstract We report the results of ^{12}CO and ^{13}CO J=1–0 observations of eight candidates of Ultra-Compact (UC) HII regions with the Purple Mountain Observatory (PMO) Qinghai 13.7 -m telescope, which resulted in revealing 11 molecular cores. Their masses range from 130 to $1.7\times10^4\,M_\odot$, with different spatial scales ($1 \sim 6$ pc). Also presented are the relevant HCO$^+$ J=1–0 maps, which enabled us to investigate more detailed structures of these cores. Further comparisons show that four of the cores deviated from the centers of infrared (MIR) emission of Midcourse Space Experiment (MSX), while others correspond either to bright MIR sources or diffuse MIR background. This indicates various evolutionary phases of the cores, including quite early ones for those without MIR sources.

Key words: stars: formation — ISM: clouds — ISM: molecules — ISM: evolution

1 INTRODUCTION

Massive star formation (MSF) is on the frontier of astrophysics for its essential impacts on ISM and galactic evolution. However, due to many observational difficulties, the theory of MSF is still far from maturity. Hence searching for samples of MSF and establishing its evolutionary sequence are very important. As an example, with CO isotopic mapping and archive data of CS (7–6), Zhou et al. (2005) suggested an evolutionary sequence for molecular cores traced by H_2O masers cores in different evolutionary stages are identified (e.g. Zhu et al. 2006, Zhou et al. 2005).

As the seedbed of stars, molecular clouds contain plentiful complexes which include objects in various evolutionary stages. While usually UC HII regions are used as the signs of evolved star formation regions, it is interesting to investigate whether earlier objects can be found in the same regions. In this connection, some very young massive stellar objects were found (Wu, Zhu et al. 2005; Birkmann et al. 2006).

In this letter, we report our millimeter observations of eight regions traced by luminous IRAS sources according to the criteria of Wood & Churchwell (1989) (WC criteria hereafter), a criteria usually used to identify candidates of UC HII regions. Ten ^{13}CO molecular cores were found and further investigated through observation with a high-density probing (HCO$^+$) and comparison with MIR images.

Section 2 describes our observations, including CO isotopes and HCO$^+$ J=1–0 lines. Then the results of these observations are presented and discussed in detail in Section 3, and finally Section 4 states the conclusions.

2 OBSERVATIONS

The CO isotopic J=1–0 lines were observed with the PMO 13.7-m telescope at the Qinghai Station in December 2004 and May 2005. During the observations ^{12}CO, ^{13}CO and C^{18}O lines were received simultaneously by a superconductor receiver, while the C^{18}O signals were too weak to provide useful information. At the wavelength of 2.6 mm, the beam size was 50 arcsec, and a step length of 60 arcsec was chosen

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for the mapping. The system temperature was about 200–210 K, and the total bandwidths were 145.4 for ^{12}CO and 42.9 MHz for ^{13}CO, corresponding to velocity resolutions of 0.37 and 0.12 km s^{-1}. The pointing accuracy of the telescope was better than 10 arcsec, and the main beam efficiency was about 0.71.

In April and May 2005, further HCO$^+$ J=1–0 observation was made with beam size 1 arcmin and step length 30 arcsec, i.e., in the full-map mode. The velocity resolution was 0.14 km s^{-1} and the system temperature was 220–245 K. All the data and images were reduced with CLASS and GREG of GILDAS.

3 RESULTS AND DISCUSSION

3.1 Mapping and Physical Results

As mentioned above, eight sources, including a known UC HII region G61.59–0.1, were observed with ^{13}CO J=1–0 lines and 10 ^{13}CO cores were revealed. These sources and cores are listed in Table 1, and also presented are their line parameters.

Table 1 Observational and Physical Parameters of the ^{13}CO Molecular Cores

Sources	α(2000.0) h m s	δ(2000.0) ° ′ ″	T_A^* K	V_{LSR} km s^{-1}	ΔV km s^{-1}	D kpc	T_{ex} K	R pc	$N(H_2)$ 10^{22}cm^{-2}	$n(H_2)_{peak}$ 10^3 cm^{-3}	M $M_\odot$
00557+5612–N	00 58 44.4	56 28 16	3.51	–30.4	1.84	2.72	14.3	1.48	0.70	3.29	571
00557+5612–SW	00 58 44.4	56 28 16	3.26	–30.2	1.54	2.72	13.9	0.89	0.66	2.73	179
01056+6256	01 08 48.5	63 07 18	1.61	–43.3	1.54	4.19	9.6	3.35	0.20	0.81	597
03235+5808	03 27 21.4	58 19 22	2.48	–47.0	2.49	4.92	13.5	3.27	0.60	1.91	2680
04001+5052	04 03 49.4	51 00 48	2.31	–33.0	2.49	4.54	9.6	2.81	0.45	1.46	1530
04323+5106	04 36 19.7	51 12 44	3.42	–36.7	3.47	5.93	14.9	6.04	1.17	2.79	7590
18556+0136	18 58 13.1	01 40 35	7.67	33.1	5.57	2.00	34.9	2.33	8.88	57.2	17100
G61.59–0.1–E	19 47 48.2	25 12 50	2.72	19.4	1.59	1.69	12.8	1.19	0.42	3.29	178
G61.59–0.1–W	19 47 48.2	25 12 50	2.86	18.8	1.63	1.69	11.9	0.86	0.50	3.96	129
22308+5812	22 32 46.0	58 28 22	2.62	–52.6	2.72	5.69	14.0	3.52	0.72	1.80	3897

Figure 1 presents three sample ^{13}CO maps. The contours of 50% level of the peak intensities were used to define the boundaries of the cores. However, for the case of multiple cores, definition with higher contours was used.

The physical parameters of the cores were estimated and presented in Table 1. Excited temperatures, which are also the kinetic temperatures under the assumption of Local Thermal Equilibrium (LTE), were evaluated from the ^{12}CO lines at the core centers. The results are from about 10 to 15 K except for IRAS 18556+0136. In fact, this source coincides in position with the G35.2–0.74 HII region complex (Dent et al. 1984), which is a quite evolved star formation region with a high activity of star formation indicated by outflows of some additional components (Wu, Zhang et al. 2005).

Assuming the ^{13}CO lines to be optically thin and [^{13}CO]/[H_2] = 1.12×10^{-6}, the column densities can be estimated. Except for IRAS 18556, the results range from 10^{21} to 10^{22} cm^{-2}, which are just about the critical value of collapse given in Hartquist et al. (1998).

With the distances obtained from fitting the Galactic rotational curve, the masses of the cores were estimated: these range from 130 to $1.7\times10^4\,M_\odot$, and seven of them were larger than 500 $M_\odot$.

3.2 Evolutionary Stages

To investigate the evolutionary stages of these cores, the ^{13}CO maps were compared with the MIR images of MSX and the point source catalogs of MSX and IRAS. A diversity of the mm-IR relationship was found. Four sources (IRAS 01056, 04001 (Fig. 1a), 03235 and 18556) each contain a single core located in region of bright IR emission. It is more attractive if the core deviated from the IR emission, as exemplified by G61.59 (Fig. 1b): two molecular cores were revealed above clear backgrounds in all the four bands of MSX, suggesting quite early phases for them. Similar cores were also reported in the J=1–0 mapping of ^{13}CO (Wu et al. 2001) and ^{12}CO (Shepherd & Churchwell 1996). All these indicate that despite their relative low excited densities, CO isotopes are still good tracers of early cores.

Meanwhile, for three other sources (IRAS 00557, 04323 and 22308 (Fig. 1c)), it is difficult to judge the relation between the ^{13}CO and IR emissions (Fig. 2), indicating that molecular lines with higher density are

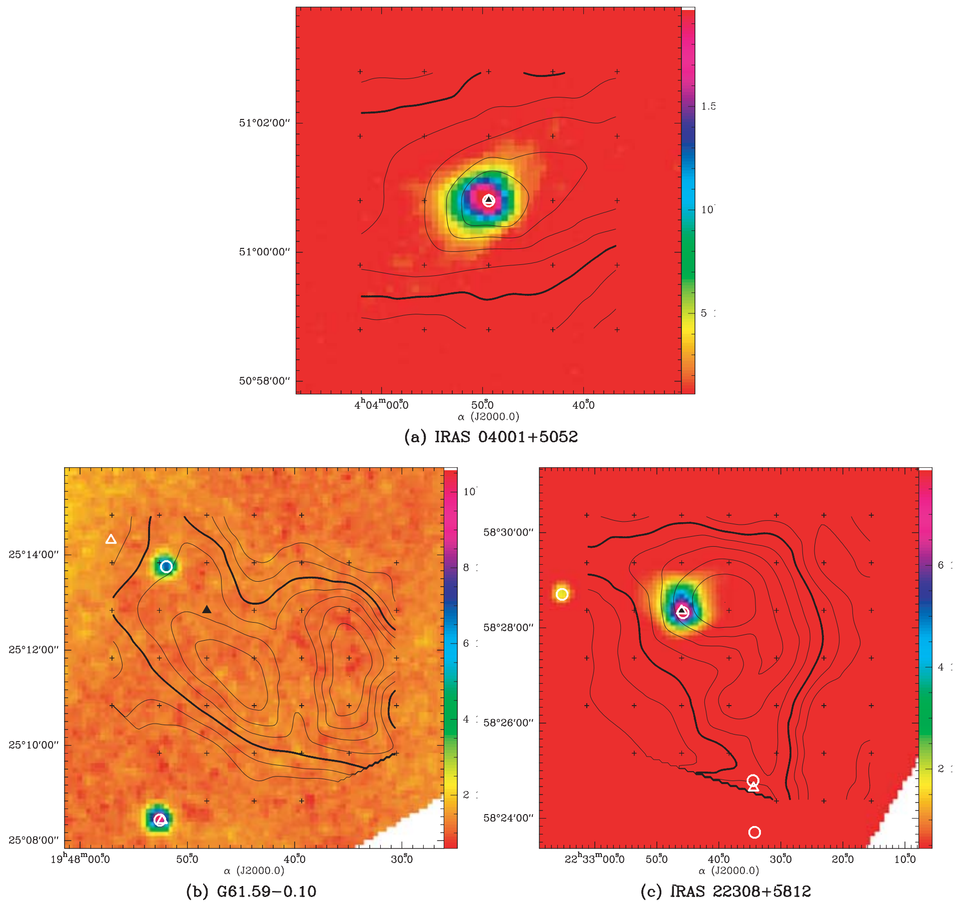

Fig. 1 ^{13}CO integrated maps (contours) overlapped on MSX A band (8 μm) images. (a)–(c): IRAS 04001, G61.59 and IRAS 22308. ^{13}CO contours are from 20% to 90%, and the thick ones show the 50% level. The black triangles mark the (0, 0) points, the white triangles and circles are IRAS and MSX point sources.

necessary. In our work HCO^+ J=1–0 lines were observed in the central parts of the three sources, and the mapping results (Fig. 2) clearly show that the compact HCO^+ cores are absolutely consistent with ^{13}CO cores and away from IRAS sources or the MSX MIR emission, if any.

The HCO^+ map of IRAS 00557 shows an additional core of low ^{13}CO emission. We suggest it might be that the HCO^+ core had lost its outer cooler envelope so the relative intensity of HCO^+ to ^{13}CO was strengthened. This phenomenon might indicate very different radial density profiles for the additional HCO^+ core and the ^{13}CO main core.

4 CONCLUSIONS

With the aim of finding molecular cores which will ultimately form stars but at present are still in their very early evolutionary phases, we observed the ^{13}CO and HCO^+ J=1–0 lines in regions traced by luminous IRAS sources. As a result, 11 molecular cores (10 in ^{13}CO and another in HCO^+) in eight sources were revealed, which apparently indicates that the molecular cores near mature star formation regions are common.

We found that there is quite a large portion (4/10) where the core deviates from the IR emission, while in the others, the core is consistent in position with the IR sources or diffuse IR emission. Such complex relationships reflect different evolutionary stages, and imply the feasibility of our means of investigating the sequence of MSF. Our work shows that CO isotopes could be used as an effective means to search

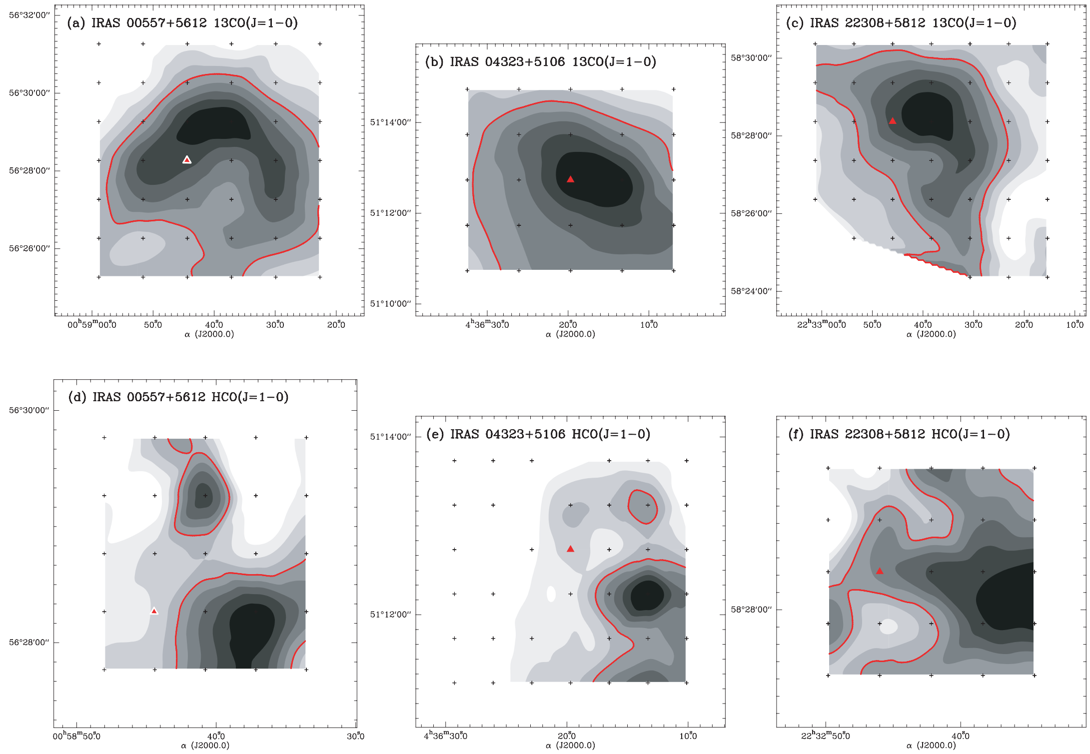

Fig. 2 (a)–(c): ^{13}CO maps of IRAS 00557, 04323 and 22308; (d)–(f): Corresponding HCO^+ maps of the three sources. Contours are from 20% to 90%, and the thick ones show 50% level. The triangles mark the (0, 0) points, also the positions of IRAS sources.

primordial molecular cores, although the molecular lines with higher excitation density, such as HCO^+, are more powerful. Meanwhile, our observation also indicates that even in the vicinities of relative evolved star formation regions (the IRAS bright sources which meet the WC criteria) such cores are still can be found.

Finally, for effective statistic research more surveys are indispensable to gather larger samples. Especially, more observations with high density line probes and interferometers of molecular cores in early phases will be very precious for revealing their detailed internal structures.

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