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ORIGINAL ARTICLE

A new evolutionary scenario of intermediate-mass star-formation revealed by multi-wavelength observations of OMC-2/3

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Abstract We have performed millimeter- and submillimeter-wave survey observations using the Nobeyama millimeter array (NMA) and the Atacama Submillimeter Telescope Experiment (ASTE) in one of the nearest intermediate-mass (IM) star-forming regions: Orion Molecular Cloud-2/3 (OMC-2/3). Using the high-resolution capabilities offered by the NMA (∼several arcsec), we observed dust continuum and $H^{13}CO^+$(1–0) emission in 12 pre- and proto-stellar candidates identified previously in single-dish millimeter observations. We unveiled the evolutionary changes with variations of the morphology and velocity structure of the dense envelopes traced by the $H^{13}CO^+$(1–0) emission. Furthermore, using the high-sensitivity capabilities offered by the ASTE, we searched for large-scale molecular outflows associated with these pre- and proto-stellar candidates observed with the NMA. As a result of the CO(3–2) observations, we detected six molecular outflows associated with the dense gas envelopes traced by $H^{13}CO^+$(1–0) and 3.3 mm continuum emission. The estimated CO outflow momentum increases with the evolutionary sequence from early to late type of the protostellar cores. We also found that the 24 μm flux increases as the dense gas evolutionary sequence. We propose that the enhancement of the 24 μm flux is caused by the growth of the cavity (i.e. the CO outflow destroys the envelope) as the evolutionary sequence. Our results show that the dissipation of the dense gas envelope plays an essential role in the evolution of the IM protostars. The extremely high-sensitivity and high-angular resolution offered by ALMA will reveal unprecedented details of the inner ∼50 AU of these protostars, which will provide us a break through in the classic scenario of IM star/disk formation.

Keywords IM protostars · Molecular outflows

1 Introduction

In the last two decades, the development of millimeter interferometers has enabled us to establish a standard scenario of sun-like ($M_*{\sim}1M_\odot$) star formation. However, details of formation and evolution of more massive stars ($\geq 2M_\odot$), that is, intermediate- and high-mass protostars, remain poorly understood. Studies of the formation and evolution of IM protostars will allow us to understand whether the established low-mass star-formation scenario is applicable to a wide range of protostar masses. However, there is no systematic observations toward IM protostars. It is important to directly verify the accretion and dissipation (or destruction) processes of dense gas envelopes around IM protostars. For these purposes, we have performed multi-wavelength and multi-line survey observations toward IM pre- and protostellar candidates in the OMC-2/3 region.

The OMC-2/3 region ($d = 450$ pc; Genzel and Stutzki 1989), which is located at the northern part of Orion A

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Table 1 NMA Observational Parameters

	$H^{13}CO^+$(1–0)	3.3 mm
Velocity resolution ($km\,s^{-1}$)	0.1	–
Rms noise level (Jy $beam^{-1}$)	0.1	0.001
Primary beam (HPBW in arcsec)	77 (3500 AU)	
Spatial resolution (arcsec)	3.5–6.0 (1600–2700 AU)	

giant molecular cloud, is one of the nearest active star-forming regions. There are 28 millimeter- and 33 submillimeter dust condensations in this region (Chini et al. 1997; Lis et al. 1998; Nielbock et al. 2003). Six condensations are associated with class 0-type SEDs by the $L_{\rm bol}/L_{\rm smm}$ diagnose (Chini et al. 1997). In addition, the bolometric luminosity and core mass of these sources are at least one order of magnitude larger than low-mass counterparts, suggesting that these sources potentially form IM protostars (2–3$M_{\odot}$ or a A0 star at the ZAMS).

2 Observations

We have observed the $H^{13}CO^+$ ($J = 1$–0; 86.754330 GHz) emission and the 3.3 mm continuum emission toward 12 millimeter sources in the OMC-3 region (SIMBA *a* and MMS 1 to MMS 10) and northern part of the OMC-2 region (FIR 2) with the six-elements NMA C+D configurations from 2004 November to 2006 May. The NMA observational parameters are summarized in Table 1. The CO(3–2; 345.795990 GHz) data have been taken with the ASTE 10 m telescope located at the Pampa la Bola, Chile during the period of 2005 September. The On-The Fly (OTF) mapping technique was employed to cover the entire OMC-2/3 region. The effective FWHM resolution is 26″ (corresponding to 0.06 pc). The typical rms noise level was 0.47 K in T_A^* with a velocity resolution of 1.08 $km\,s^{-1}$. In order to identify protostars along the OMC filament, we have also fetched archived 24 μm data obtained by infrared camera MIPS (Multiband Imaging Photometer) equipped in the infrared space telescope Spitzer.

3 Survey results

Figure 1b shows distribution of the CO(3–2) high-velocity emission in OMC-2/3. We totally identified 14 outflows and eight of them are newly identified in the present study (the detailed results of the CO(3–2) emission taken with the ASTE telescope will be in the forthcoming paper). Specifically, eight out of the fourteen outflows, SIMBA *a* and *c*, MMS 2, MMS 5, MMS 7, MMS 9, FIR 2, FIR 6*b*, and FIR 6*c* are accompanied with the 1.3 mm dust condensations taken with the single-dish observations, and 24 μm Spitzer sources, suggesting the presence of the heating sources.

We have detected the compact 3.3 mm continuum emission (i.e., thermal dust emission) with a size scale of a few × 1000 AU toward the eight 1.3 mm sources, SIMBA *a*, MMS 1, MMS 2, MMS 5, MMS 6, MMS 7, MMS 9 and FIR 2 using the NMA. Seven out of the eight 3.3 mm sources (i.e., except MMS 1) are associated with the 24 μm Spitzer sources.

Figure 1c shows integrated intensity maps of the $H^{13}CO^+$ emission taken with the NMA. Significant $H^{13}CO^+$(1–0) emission has been detected toward nine out of the twelve 1.3 mm sources, SIMBA *a*, MMS 1, MMS2, MMS 3, MMS5, MMS6, MMS 7, MMS 8, and FIR 2, with a size and mass scales of 0.01–0.1 pc and 0.5–5$M_{\odot}$, respectively. The detected $H^{13}CO^+$ envelopes show various morphologies (centrally condensed, fan-shaped structure, etc.).

Velocity gradients along the major axis, implying rotating motion, are detected toward 5/12 sources. This velocity gradient was detected toward both pre- and proto-stellar candidates. In addition, along the minor axis in the $H^{13}CO^+$ envelope, we detected the gas dispersing motion along and/or perpendicular to the outflow axis toward 4/12 samples. This velocity gradient was only detected toward protostellar candidates. On the other hand, there is no clear evidence of gas accreting motion in the $H^{13}CO^+$ emission. From the intensive survey, we unveiled presence or absence of the molecular outflows and central protostars toward millimeter condensations in the OMC-2/3 region, and also revealed spatial- and velocity- structure of the associated dense gas envelopes traced by the $H^{13}CO^+$(1–0) emission.

4 Discussion

In order to discuss the evolutionary sequence of the IM protostars, we used six independent multi-wavelength data, our $H^{13}CO^+$(1–0) and 3.3 mm continuum emission, CO(3–2) emission and JHK_s images taken with the SIRIUS/IRSF, archive 24 μm Spitzer data, and published VLA-3.6 cm data from (Reipurth et al. 1999). $H^{13}CO^+$(1–0) emission traces a distribution and kinematics of the dense gas envelope. The size and momentum of the molecular outflows traced by the CO(3–2) emission reflect the age (or) activity of the CO outflow. 3.3 mm and 24 μm compact continuum sources trace a region, which is dense ($\geq 10^7$ cm^{-3}) and hot (>150 K) inner envelope associated with the protostars. Reflection nebula (i.e., cavity-like structure along the molecular outflow) in JHK_S images is related to the dissipation of circumstellar material. Further free-free jet traced by the VLA-3.6 cm emission show an activity of central jet.

"Pre-stellar" sources, MMS 4, MMS 8 and MMS 10, have no 3.3 mm and 24 μm compact sources above 3σ sig-

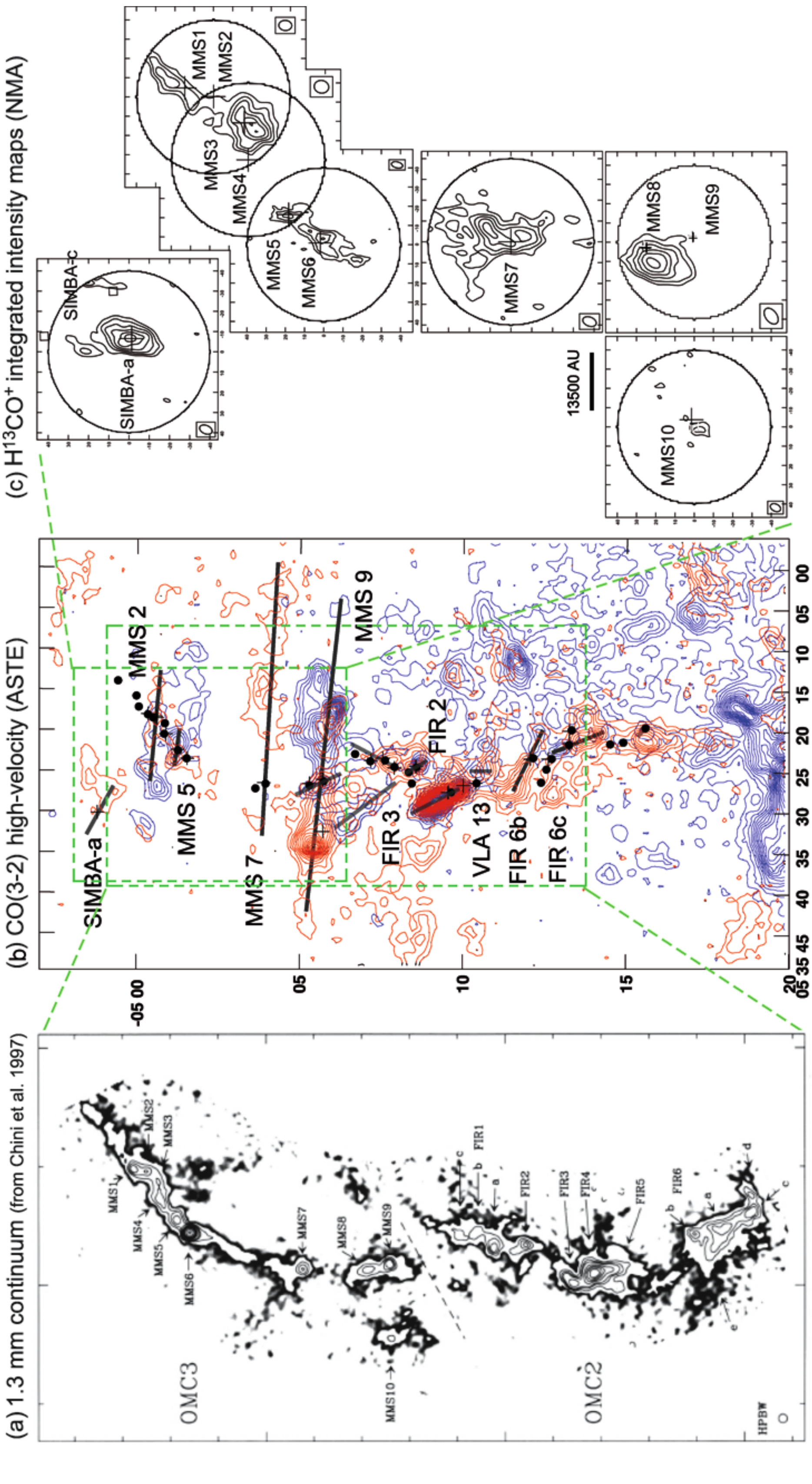

Fig. 1 **a** A 1.3 mm map of the OMC-2 and -3 region from Chini et al. (1997). **b** Survey results of molecular outflows traced by the high-velocity CO(3–2) emission taken with the ASTE with a velocity range of $Vlsr = -6.2$ to $7.8\ \mathrm{km\,s^{-1}}$ (*blue*) and $Vlsr = 14.3$ to $27.3\ \mathrm{km\,s^{-1}}$ (*red*), respectively. **c** Survey results of dense envelopes traced by the $H^{13}CO^{+}$(1–0) emission taken with the NMA. *Crosses* in (**b**) and (**c**) show the positions of the 1.3 mm source (from Chini et al. 1997). *Dots* in (**b**) show the positions of the 350 μm source (from Lis et al. 1998)

nal level, suggesting no signature of the dense and hot inner envelope. Upper-limit of average densities estimated by the 3.3 mm compact dusty component, several $\times 10^6$ cm^{-3}, is typically one order of magnitude less than that of protostellar samples in OMC-2/3 (a few $\times 10^5$ cm s^{-3}). In this phase, there is no signature of jet and outflow. These objects are associated with the relatively extended $H^{13}CO^+$(1–0) component(s).

"Class A" sources, SIMBA *a*, MMS 5 and FIR 2 are associated with 3.3 mm and faint 24 μm compact sources, suggesting the presence of the dense and inner hot envelope. Further 0.1 pc-scale CO outflow is detected toward each object. These results imply that protostars are already formed in central region and may begin mass accretion, although we did not detect mass accretion directly. Detected velocity gradient along the major axis implies the rotational motion of the envelope traced by the $H^{13}CO^+$ emission. We also found an evidence the dense gas traced by the $H^{13}CO^+$ emission entrained by the CO outflow. In this phase, we did not detect signature of free–free jet and reflection nebula.

"Class B" sources, MMS 2, MMS 7 and MMS 9 are associated with 3.3 mm and bright 24 μm compact sources, suggesting presence of the dense and hot envelope. Both of a 0.5–1.0 pc scale of CO outflow and free–free jet are associated with the objects. In addition, JHK_s images show reflection nebula around the heating source, suggesting the formation of the cavity along the outflow axis. Fan-shaped structure traced by the $H^{13}CO^+$ emission with a size scale of 0.1 pc have been observed in this phase. The peak position of the $H^{13}CO^+$ emission does not coincide with the 3.3 mm continuum emission.

From these results, we consider that the above classification with observational results suggest the formation scenario of the IM protostars with dissipating processes of circumstellar materials. Since protostars are formed in denser region ($\geq$a few $\times 10^7$ cm^{-3}) traced by the 3.3 mm continuum emission taken with the NMA, inner hot envelope are observed by the 24 μm emission. Class A corresponds to the earlier evolutionary stage of the proto-stellar core with a rotating envelope traced by the $H^{13}CO^+$(1–0) emission. In this phase, small scale outflow with a size scale of 0.1 pc is observed. Class B corresponds to the later evolutionary stage of the proto-stellar cores. We detected dense gas dissipation in $H^{13}CO^+$(1–0) emission toward MMS 2 and MMS 7 (Detailed descriptions are in Takahashi et al. 2006). On the other hand, we did not detect significant $H^{13}CO^+$ emission toward MMS 9, implying dissipation of the dense gas. In Class B, large scale outflows (0.5–1 pc) are observed.

Furthermore we found the relation between the outflow growth and evolution of the circumstellar gas. Figure 2 shows a 24 μm flux densities plotted as a function of the outflow momenta derived from CO(3–2) observations. Our results show that the 24 μm flux has a positive correlation with the CO outflow momentum except for one object. In addition, Objects with the higher CO outflow momentum and 24 μm flux denoted by a shaded area in Fig. 2, are associated with a cm jet and bright reflection nebula in the NIR image. The presence of the cm jet and NIR nebula implies the formation of cavities along the outflow axis and the dissipation of the dense gas envelope. These phenomena are consistent with the dense core dissipation from Class A to ClassB denoted by Fig. 2. We consider that the dissipation of the dense gas plays an essential role in the evolution of the IM protostars.

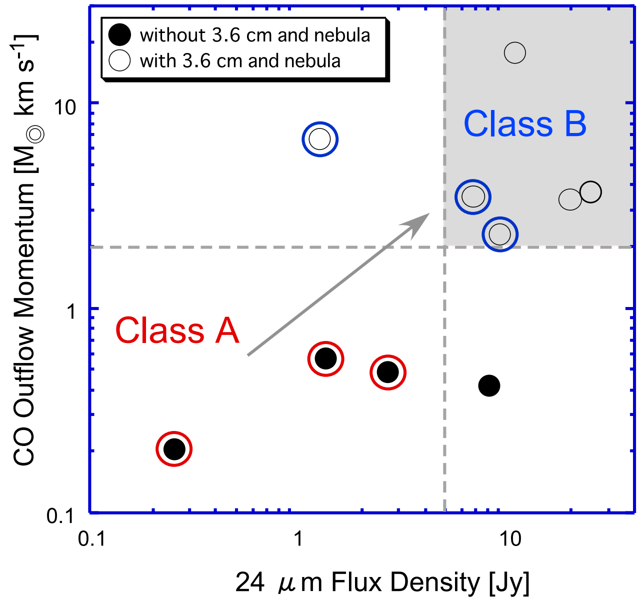

Fig. 2 The outflow momentum derived by CO(3–2) emission plotted as a function of the 24 μm flux

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