Dense Shell around a Young Intermediate-Mass Star NGC 2264 IRS1 *

Makoto Nakano
Faculty of Education and Welfare Science, Oita University, Oita 870-1192, Japan
mnakano@cc.oita-u.ac.jp

Koji Sugitani
Institute of Natural Sciences, Nagoya City University, Mizuho-ku, Nagoya 467-8501
sugitani@nsc.nagoya-cu.ac.jp
and

Koh-Ichiro Morita
Nobeyama Radio Observatory, Minami-saku, Nagano 384-1305
morita@nro.nao.ac.jp

(Received 2002 August 26; accepted 2002 December 13)

Abstract

The results of H13CO+ J=1-0 line and 93-GHz continuum observations of NGC 2264 IRS1, the luminous infrared source known as Allen’s source, are reported. IRS1 is a young intermediate-mass star with a surrounding YSO cluster around, and is associated with a molecular outflow. High angular resolution interferometric observations were performed using the Nobeyama Millimeter Array, and mapping observations were conducted using a 45-m telescope. The continuum map reveals four sources, three of which correspond to the submillimeter source detected by Ward-Thompson et al. (2000). Four compact clumps are also detected in the H13CO+ map, two of which are associated with these millimeter/submillimeter continuum sources without bipolar outflow. These H13CO+ clumps as a whole form an incomplete dense shell of 0.12 pc in diameter around IRS1, and the outer part of the shell is clearly traced on the single-dish map. The shell or cavity structure suggests that the outflow from IRS1 has evacuated part of the surrounding envelope in \( \sim 0.1 \) Myr. The kinematic properties can be interpreted as two clumps of entrained or compressed material derived from the steady outflow. It is concluded that the activity of IRS1 may have triggered the formation of cluster members in the dense surrounding shell.

Key words: Galaxy: open clusters and associations: individual (NGC 2264)—ISM: clouds—ISM: molecules—stars: formation—stars: pre-main sequence

1. Introduction

Recent high-resolution millimeter and submillimeter observations have revealed the dynamic structure and density distribution in low-mass star-forming regions such as the Taurus and Ophiuchus regions. These observations have been confronted with the predictions by theoretical models. Consequently, our understanding of low-mass star formation processes has advanced considerably in recent years (e.g., Andrè et al. 2000). Studies of regions forming intermediate-mass stars (a few \( M/\)M\(_\odot\) < 10), based primarily on observations of Herbig Ae/Be (HAEBE) stars, are in a different situation. Such systems are not uniform, particularly compared to T Tauri type stars, and the mechanisms remain contentious (Natta et al. 2000). The circumstellar disk around B type stars revealed by millimeter wave observations is unexpectedly small (log \( M_{\text{disk}}/M_{\text{star}} \) \( \leq -2 \)), and the clustering properties around the young HAEBE intermediate-mass stars have been characterized through extensive near-infrared imaging of the surrounding fields (Testi et al. 1999). However, the relatively short evolutionary timescale of these stars and the presence of obscuring dense cores prevents the early stages of formation from being fully traced. In this context, high spatial resolution observations of intermediate-mass stars in the early evolutionary stages are important in developing a comprehensive understanding of the formation mechanism of both the star itself and the surrounding cluster.

NGC 2264 is a young open cluster of about 3 Myr in age located at a distance of 800 pc (Walker 1956). NGC 2264 contains relatively few massive stars compared to other high-mass star-forming regions such as Ori OB1. Margulis et al. (1988) performed an unbiased survey on molecular outflows, and discovered many outflows. It was subsequently suggested that 50% of the bright Infrared Astronomical Satellite (IRAS) sources \( (L_{\text{bol}} > 50 L_{\odot}) \) in this region are related to these outflow sources (Margulis et al. 1989). Among them, the brightest source \( (2300 L_{\odot}) \) is NGC 2264 IRS1, known also as Allen’s source (Allen 1972). The bolometric luminosity of IRS1 corresponds to that of a ZAMS B2 type star of 5–6 \( M_{\odot} \) crossing the birthline towards the main sequence on the Hertzsprung-Russell (HR) diagram. Since IRS1 is relatively isolated
(about 1' or more) from other known pre-main sequence stars in NGC 2264 (Wolf-Chase & Gregersen 1997), the influence from other young stellar objects (YSOs) can be neglected, which is advantageous for high-resolution observations. The spectral energy distribution suggests that IRS1 is a Class I-like source (Margulis et al. 1989), and is very bright in the near-infrared despite large extinction (Allen 1972). The CS J=7-6 emission line, which traces the high-density region, has revealed a pseudodisk structure of 0.3 pc in size (Wolf-Chase et al. 1995), and a jet-like feature has been identified in the infrared (Schreyer et al. 1997). Recently, Nakano et al. (2000) performed hard X-ray observations, a powerful tool for detecting young objects deeply embedded in clouds, of the region encompassing NGC 2264 IRS1 using the Advanced Satellite for Cosmology and Astrophysics (ASCA).

Ward-Thompson et al. (2000, hereafter W00) discovered a ridge of emission, NGC 2264 MM, containing a cluster of five sources by 350 μm to 1.3 mm continuum observations. The mass of each source was found to be equivalent to up to 50 solar masses, and each is anticipated to host a massive star or group of stars. These features make NGC 2264 IRS1 a good site for the study of cluster star formation, and as such has been the focus of many observations (e.g., Lada et al. 1993). However, no molecular line observations obtained at high spatial resolution have been reported to date. This paper reports on high-resolution observations of the NGC 2264 IRS1 region in the millimeter continuum and the H$_{13}$CO$^+$ line, which is an excellent tracer of the high-density region.

2. Observations

2.1. Interferometric observations

High angular resolution interferometric observations were made using the Nobeyama Millimeter Array (NMA) of 6-element antennas in March and April 2000. Two different array configurations (C and D) were employed, yielding baselines in the range 2.9-47.2 kλ. An FX spectrometer with 1024 channels and a bandwidth of 32 MHz was employed as a back end, covering a velocity range of 110 km s$^{-1}$. Two channels were combined to achieve a velocity resolution of 0.2 km s$^{-1}$ for observations of H$_{13}$CO$^+$ J=1-0 (86754.33 MHz). A 256-channel ultrawide band correlator (UWBC) with a spectrum of 512 MHz was employed as a back end, covering a velocity range of 110 km s$^{-1}$. Half power beam width (HPBW) was 19$''$. The velocity resolution was 0.1 km s$^{-1}$, and the half power beam width (HPBW) was 19$''$ at 87 GHz. A 2'×2' map was made of the region of IRS1, with a grid spacing of 10$''$.3. Mapping was performed by position-switching with an integration time of 260 s per position. The pointing accuracy was checked every 1-2 h using the SiO maser source GX Mon, and was confirmed to be better than 5$''$. The intensity was calibrated by the standard chopper-wheel method. The main beam efficiency at 86 GHz was 0.49.

3. Results

3.1. Continuum map

The 93-GHz continuum map drawn with uniform weighting using the interferometer is shown in figure 1. The HPBW of the synthesized beam and the primary beam response are 3$''$.94×3$''$.00 (PA=140.8°) and 81$''$, re-

![Fig. 1. 3.5-mm continuum map. Contours are spaced at 3.0 mJy beam$^{-1}$ intervals, and the lowest contour is at the 3.0 mJy beam$^{-1}$ level. Negative contours are shown as dashed lines. IRS1 is at the center of the map (indicated by a star symbol), and crosses indicate the position of submillimeter continuum sources (Ward-Thompson et al. 2000). The synthesized beam is shown at the lower left corner. The half-power width of the primary beam of an element antenna is indicated by the circle.](image-url)
spectively. The 1σ rms noise is 1.5 mJy beam$^{-1}$. Four continuum sources with sizes of 2$''$–5$''$ (=1600–4000 AU) were detected, with parameters as shown in table 1. Three of the sources correspond to the submillimeter sources MMS3, 4, and 5, to the southeast of IRS1 (W00, pointing accuracy better than 3$''$). These three sources are located in the central region of NGC 2264 MM. W00 suggested that each of the submillimeter sources represents the formation of one or more intermediate- or high-mass stars. In particular, MMS3, although located at the edge of the primary beam of the interferometer, produced a strong signal. An H$_2$O maser source was also identified near the position of MMS4, ~15$''$ south of IRS1 (Genzel & Townes 1977; Tofani et al. 1995), and a new continuum source (MC1) was discovered 20$''$ north of IRS1. A clue as to the nature of MC1 is given by its position; it is located on the western edge of NGC 2264 MM in figure 1 of W00, which is consistent the position of the peak in the CH$_3$OH map of Schreyer et al. (1997).

W00 described that the position of MMS5, which corresponds to one of the present continuum sources, is in agreement with that of the pre-main sequence star No. 4 detected by the Hubble Space Telescope (HST) (Thompson et al. 1998). According to the results obtained in this study, however, the positions clearly differ; MMS5 and star No. 4 are located (+10$''$4, +0$''$7) (see table 1) and (+2$''$6, −2$''$8) from IRS1, respectively. MMS5 may not be a single star, and may instead form part of the dense condensation around IRS1. The HST image exhibits a small star cluster in the vicinity of MMS3, which is also found on the near infrared (NIR) image (Hodapp 1994; Schreyer et al. 1997). There are no NIR objects near the other continuum sources.

The present 3.5-mm continuum fluxes and the single-dish fluxes obtained by W00 agree well with the spectrum for thermal dust with opacity index $\beta$ of 1.8 ($\tau = (\nu/\nu_c)^{\beta}$), and $T_{\text{dust}} = 38$ K. The gas+dust mass was estimated from millimeter continuum measurements assuming an optically thin approximation and a gas-dust ratio of 100, as suggested by W00. The adopted parameters of mass opacity and dust temperature were 0.009 g cm$^{-2}$ at 800 µm and 38 K, respectively (W00). The calculated mass of each source given in table 1 is in the range 8–13 $M_\odot$. The 3σ flux level of IRS1 corresponds to the upper limit of a mass of 2 $M_\odot$. The lack of a compact protostellar condensation implies that IRS1 is more evolved than the surrounding continuum sources.

### Table 1. Parameters of millimeter continuum sources

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MC1</td>
<td>6:41:09.6</td>
<td>+9:29:54.5</td>
<td>2.4×1.4</td>
<td>169$^\circ$</td>
<td>17.2</td>
<td>8</td>
</tr>
<tr>
<td>MMS4</td>
<td>6:41:10.0</td>
<td>+9:29:21.5</td>
<td>5.3×3.9</td>
<td>124$^\circ$</td>
<td>30.8</td>
<td>13</td>
</tr>
<tr>
<td>MMS5</td>
<td>6:41:10.2</td>
<td>+9:29:34.3</td>
<td>5.3×3.6</td>
<td>149$^\circ$</td>
<td>23.2</td>
<td>10</td>
</tr>
<tr>
<td>MMS3</td>
<td>6:41:12.3</td>
<td>+9:29:11.3</td>
<td>3.2×2.2</td>
<td>134$^\circ$</td>
<td>21.8</td>
<td>8</td>
</tr>
</tbody>
</table>

$^*$ deconvolved size
$^\dagger$ $T_{\text{dust}} = 38$ K

---

![Fig. 2. Total integrated intensity map of H$^{13}$CO$^+$ J=1-0 emission.](image)

Figure 2 shows the map of integrated intensity of H$^{13}$CO$^+$ J=1-0 overlaid on the map of single-dish data. The interferometer map was processed with natural weighting. The integration velocity range is the same for both maps, $V_{\text{LSR}} = 6.5$ to 10.8 km s$^{-1}$ with a contour spacing of 40 mJy beam$^{-1}$ starting from 40 mJy beam$^{-1}$. The synthesized beam is also shown in the lower left corner. Thin contours represent the integrated H$^{13}$CO$^+$ J=1-0 map obtained by single-dish observations. The integrated velocity range is the same as that of the map, with contours spaced at 40 mJy beam$^{-1}$ intervals starting from 512 mJy beam$^{-1}$ km s$^{-1}$. The other symbols are the same as in figure 1.

#### 3.2. H$^{13}$CO$^+$ J=1-0 map

Figure 2 shows the map of integrated intensity of H$^{13}$CO$^+$ J=1-0 overlaid on the map of single-dish data. The interferometer map was processed with natural weighting. The integration velocity range is the same for both maps, $V_{\text{LSR}} = 6.5$ to 10.8 km s$^{-1}$. NMA has a primary beam response of 86$''$, and a beam size of 4$''$84×3$''$67 (PA=143$^\circ$). The 1σ rms noise is 19 mJy beam$^{-1}$.

As was the case for the continuum emission, there is no evidence for line emission at the position of IRS1 on this map, but four clumps with sizes of 0.02–0.05 pc are present, as summarized in table 2. Two clumps (HC1 and 3) are associated with the continuum sources MMS5 and
Fig. 3. Aperture velocity channel map of H$^{13}$CO$^+$ J=1-0 emission obtained by NMA. The emission of four channels was combined to give a velocity resolution of 0.43 km s$^{-1}$. The center velocity is shown in each panel. Contours are drawn at intervals of 270 mJy beam$^{-1}$ starting from 270 mJy beam$^{-1}$. The other symbols are the same as in figure 1.
Fig. 4. Velocity channel map of $^{13}$CO+ J=1-0 emission obtained by the NRO 45-m telescope. The center velocity of each channel (0.42 km s$^{-1}$ width) is shown in each panel. Contours are drawn at intervals of 0.3 Jy beam$^{-1}$ starting from 0.88 Jy beam$^{-1}$. The HPBW is shown in the lower left corner of the top left panel. The other symbols are the same as in figure 1.

Table 2. Parameters of $^{13}$CO+ clumps

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HC1w</td>
<td>6:41:10.4</td>
<td>+9:29:39.2</td>
<td>8.6×6.0 165°</td>
<td>8</td>
<td>9.4 0.7</td>
<td>MMS5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC1e</td>
<td>6:41:11.0</td>
<td>+9:29:37.7</td>
<td>9.3×6.6 97° 97°</td>
<td>6</td>
<td>8.0 0.6</td>
<td>MMS3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC2</td>
<td>6:41:10.1</td>
<td>+9:29:48.6</td>
<td>9.8×2.8 158°</td>
<td>4</td>
<td>9.1 0.6</td>
<td>MMS2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC3</td>
<td>6:41:09.9</td>
<td>+9:29:23.2</td>
<td>7.5×5.1 84° 84°</td>
<td>6</td>
<td>9.0 0.5</td>
<td>MMS1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC4</td>
<td>6:41:08.9</td>
<td>+9:29:30.9</td>
<td>7.9×4.4 1°  1°</td>
<td>3</td>
<td>7.9 0.3</td>
<td>MMS4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^*$deconvolved size
MMS4. No outflow phenomenon has been reported for either of these sources, and both have been suggested to be pre-protostellar in nature (W00). The local standard of rest (LSR) velocity of each clump is 7.9–9.4 km s$^{-1}$, which is consistent with the previous studies conducted using single dishes (Krügel et al. 1987; Margulis et al. 1988; Wolf-Chase et al. 1995). The single-dish map in figure 2 confirms the global structure of the molecular core extending in the north-south direction $\sim 30''$ east of IRS1. Two ridges can be traces from the northern and southern ends of the core as features that curve toward the west. This core appears to correspond to NGC 2264 MM (W00), and exhibits a C-shaped ridge feature surrounding IRS1 with a diameter of 0.2 pc opening to the west. None of the four $^{13}$CO$^+$ clumps detected by interferometric observations lies on this ridge of the molecular core.

The mass of the core was calculated assuming local thermodynamic equilibrium using the equation of Aso et al. (2000), even though the single-dish observations did not cover a sufficient area of the core. An $^{13}$CO$^+$ abundance of $2 \times 10^{-11}$ (Williams & Garland 2002) and an excitation temperature of 20 K (Wolf-Chase et al. 1995) were adopted for calculation. Although the $H_2$ mass estimated from dust continuum emission may disagree with that from the $^{13}$CO$^+$ line because of the difference in tracers (Saito et al. 1999), the mass of the core, $1.5 \times 10^3 M_\odot$, is consistent with the estimate from submillimeter observations (W00) within a factor of two.

Velocity channel maps obtained by the interferometer and single-dish observations are shown in figures 3 and 4. These figures clearly distinguish the small-scale kinematic structure and the extended structure. Although MMS3 is located outside the half-power width of the NMA primary beam and is not seen in figure 2, the four associated $^{13}$CO$^+$ clumps can be confirmed in figure 3. Figure 4 reveals a smooth north-south velocity gradient. The virial mass of each clump estimated using the sizes in table 2 fall in the range $0.3$–$1.4 M_\odot$, which is several times smaller than the LTE masses. This means that all clumps appear to be in free fall. Integrating the fluxes in a box of 60$''$ $\times$ 60$''$ centered on IRS1 reveals that more than 90% of the flux obtained in the single-dish observations is missing in the interferometric observations. Thus, it remains highly uncertain whether the measured size and linewidth accurately reflect the true clump parameters. However, there is no noticeable enhancement at the position of the clumps in the single-dish velocity channel maps except for MMS3 (figure 4), which supports the hypothesis that these clumps are highly compact.

It is interesting to note that in the map in figure 2, the dense structure traced by $^{13}$CO$^+$ emission clumps also has a C-shaped form that forms a shell or cavity structure with diameter of 0.12 pc. Although the interferometer is insensitive to large-scale, smooth distributions of $^{13}$CO$^+$ emission, this feature suggests a smaller C-shaped shell immediately within the $^{13}$CO$^+$ ridge surrounding IRS1. This double C-shaped structure is consistent with the idea of small and dense condensations within the large shell.

4. Shell or cavity structure

Figure 5a shows the integrated $^{13}$CO$^+$ contours of the NMA data overlaid on the unsharp-masked negative print of an Anglo-Australian Telescope (AAT) prime-focus photograph (courtesy David Malin). A bright optical nebulosity extends northwest from the position of IRS1. A dark filamentary structure (white region in figure 5a) extends east of IRS1. Surprisingly, a good correlation can be seen between this filament and the $^{13}$CO$^+$ emission around IRS1, suggesting that IRS1 and dense clumps are located on the near side of the ambient molecular cloud core. The nearly pole-on nature of the molecular outflow (Schreyer et al. 1997) and the fact that IRS1 exhibits only a moderate extinction (Thompson et al. 1998) also support this geometry. Therefore, the structure in the interferometer map can be interpreted as an incomplete shell or cavity formed on the near side of the cloud. Furthermore, it appears that the submillimeter source MMS5 is located at the inner edge of the shell, as seen in figure 2.

As IRS1 has high bolometric luminosity, it is necessary to consider the possibility that the cavity if formed due to photodissociation of ultraviolet radiation. If IRS1 is a ZAMS B2 star, as indicated by its luminosity, the effective temperature would be 20,500 K (Panagia 1973). Although the radius of the H II region of IRS1 is negligibly small, $8 \times 10^{-4}$ pc for $n = 10^4$ cm$^{-3}$, non-ionizing photons can reasonably form a photodissociation region of 0.02 pc in size surrounding IRS1 (Diaz-Miller et al. 1998). As the initial density would be higher (Thompson et al. 1998), and considering the observation of a dense region with $n = 2$–$3 \times 10^3$ cm$^{-3}$ within a 20$''$ beam around IRS1 by Schreyer et al. (1997), the size of the photodissociation region could be considerably smaller.

The molecular outflow associated with IRS1 has been studied by many authors (e.g., Margulis et al. 1988), and Wolf-Chase & Walker (1995) discovered a dense low-velocity component of the outflow in CS emission. The redshifted gas extends $\sim 2''$ southwest of IRS1, and the blueshifted gas extends toward the east. However, the spatial resolution is not sufficiently high for a comparison with the present map. A CS J=5-4 map of higher spatial resolution of the dense outflow near IRS1 was presented by Schreyer et al. (1997), although no physical parameters of the outflow were given.

Figure 5b shows the distribution of molecular outflow in the CS J=5-4 line overlaid on the present $^{13}$CO$^+$ contours. The size of the dense outflow is comparable to that of the dense shell structure composed of three $^{13}$CO$^+$ clumps (HC1–3). The distribution of the redshifted wing is shifted slightly north of IRS1 compared with the blueshifted wing, although the both components are significantly overlapped. This direction is more or less consistent with the opening of the shell. Thus, it is reasonable to suppose that the cavity is created by molecular outflow and that the compact clumps are located at the inner edge of the shell. The kinematic structure around these bodies can also explained by this scheme.

LeFloch et al. (1998) found dust cavities of 0.1–0.2 pc
in size in NGC 1333 and discussed the possibility that the cavities were formed by outflow from YSOs. A large cavity often develops in HAEBE stars. Fuente et al. (2002) carried out systematic studies of the gas around many HAEBE stars and classified HAEBE stars into three types according to the spatial index of column density around the star. As discussion of the evolutionary sequence in terms of mass dispersal concluded that the bipolar outflow was the most promising candidate mechanism for dispersal of the surrounding envelope in the first evolutionary stages (< 0.1 Myr) of intermediate-mass stars.

5. Gas Kinematics

Figure 6 presents the position-velocity diagram along a constant declination passing through IRS1. HC1 can be seen to consist of two velocity components, HC1w and HC1e. HC1e and HC4 do not exhibit noticeable differences in velocities with respect to that of the ambient material of $V_{LSR} \sim 8$ km s$^{-1}$ (figures 3 and 4). However, HC1w and HC2 (see table 2) are redshifted by 1.0–1.5 km s$^{-1}$ with respect to the ambient velocity. Although the southern clump HC3 is also redshifted (figures 3e–3g), the velocity of the ambient material is systematically shifted to 9 km s$^{-1}$ on the single-dish map toward the south, as shown in figure 4. Wolf-Chase & Gregersen (1997) interpreted the 9 km s$^{-1}$ component seen in the CO spectrum toward IRS1 as a cool, dense shell swept up by the outflow. HC1w is the nearest clump to IRS1, and HC2 is directly associated with HC1w and overlaps the molecular outflow considerably (figures 3 and 5b). This may support the idea of interaction between the cavity wall and the outflow from IRS1. Therefore, it is suggested here that two clumps, HC1w and HC2, are entrained or compressed material formed by the steady outflow from IRS1. The

![Figure 5](image_url)

**Fig. 5.** $^{13}$CO$^+$ map overlaid on (a) an unsharp-masked negative red image (© Anglo-Australian Observatory) and (b) the distribution of molecular outflow in the CS J=5-4 line (Schreyer et al. 1997). Thin dashed lines denote blue wing emission, and thin solid lines indicate red wing emission.

![Figure 6](image_url)

**Fig. 6.** Position-velocity diagram of $^{13}$CO$^+$ emission along a line passing through NGC 2264 IRS1 at the position angle of 90°. Contours are spaced at 126 mJy beam$^{-1}$ intervals, and the lowest contour is at 187 mJy beam$^{-1}$. The single-dish data are shown as thin contours spaced at intervals of 200 mJy beam$^{-1}$ starting from 320 mJy beam$^{-1}$. Dashed lines denote the velocity range used to construct the integrated intensity map in figure 2.
compact clumps at the inner boundary of the shell also supports this idea.

Williams & Garland (2002) obtained HCO$^+$ and H$^{13}$CO$^+$ J=3−2 spectra for NGC 2264 MM and attempted to explain the results using a simple, one-dimensional radiative transfer model. They suggested that the outer layer is collapsing onto an expanding inner region, with a boundary between the inner and outer layer at r = 1×10$^{18}$ cm (50″ at 800 pc), which is almost coincident with the size of the primary beam response of NMA. On the submillimeter maps of W00 and Williams & Garland (2002), IRS1 itself is located at the western edge of NGC 2264 MM. If the kinematic model of Williams & Garland (2002) is applicable for the entire NGC 2264 MM ridge, IRS1 and MMS3 appear to be the sources of expanding motion. Unfortunately, NGC 2264 MM has a rather complex structure, and the present NMA observations do not fully cover the MMS3 region. Therefore, the discussion here is limited to the immediate vicinity of IRS1. It can be speculated that the gas within the cavity is of low density and is expanding due to molecular outflow originating from IRS1. The possible existence of expanding gas around IRS1 could not be verified from the present observations because both interferometer and H$^{13}$CO$^+$ emission analyses are insensitive to the extended gas component. If dense clumps make up part of the shell structure on the near side of the ambient cloud along the line of sight, the redshifted velocity will indicate falling motion toward IRS1. The presence of infall motion toward IRS1 has also been suggested by Wolf-Chase & Gregersen (1997). Thus, there remains another possibility that HC1w and HC2 are inner parts of the shell falling inward toward IRS1.

The CS linewidth at the zero intensity level of the dense outflow was reported by Wolf-Chase et al. (1995) to be 12.0 km s$^{-1}$, and the velocity of HC1w and HC2 is 1.0−1.5 km s$^{-1}$ with respect to the ambient velocity as previously shown. Furthermore, on the scale of the envelope around IRS1, Williams & Garland (2002) calculated an expansion velocity of 1 km s$^{-1}$. Thus, it is reasonable to assume that the expansion velocity of the shell is 1−2 km s$^{-1}$. The time required to gouge out a cavity of radius 0.06 pc is calculated to be $\sim 6 \times 10^4$ yr. As the outflow phenomenon prevails during the very earliest phases of the star formation process (Richer et al. 2000), this cavity formation time is consistent with the evolutionary time of IRS1, 1.5 $\times 10^5$ yr, as estimated by Thompson et al. (1998).

HCO$^+$ enhancement by shock-induced chemistry was proposed by Girart et al. (2000) in the case of NGC 2264G. However, the CS (Schreyer et al. 1997) and HCO$^+$ (Williams & Garland 2002) abundances are largely uniform around IRS1. Thus, there appears to be no clear evidence that shock chemistry from IRS1 plays an important role in the appearance of this cavity. High-resolution studies for other molecular transitions such as SiO are required to trace the shock condition (Mikami et al. 1992; Codella et al. 1999).

6. Cluster formation

As clusters are often found around young B type stars, star formation by the cluster mode appears to hold for intermediate-mass stars. Some early-type Herbig Be stars are surrounded by rich clusters, and Testi et al. (1999) reported that these stars have a richness indicator ($I_c$), the integral over distance of the source surface density profile corrected for the background source density, of $> 40$. In the case of NGC 2264 IRS1, there is a cluster of NIR sources with $I_c$ of 66 (Nakano et al. 2000). However, it appears that IRS1 is relatively isolated (Wolf-Chase & Gregersen 1997), and that the surface density of sources decreases rather than increases within 30″ radius from IRS1. This is probably due to the fact that the dense shell around IRS1 obscures some of the cluster members, and/or that cluster formation is still in progress in the shell.

Six low-mass pre-main sequence stars have been discovered in close association with IRS1, with a projected separation of 3″−5″ on the southeastern side. Thompson et al. (1998) suggested that IRS1 triggered the formation of the small cluster of low-mass stars. The stars are roughly arranged in an arc on the side facing the dense clumps. To date, no other YSO candidates have been reported within the area of the present interferometer observations. These results are also consistent with the presence of a dense shell surrounding IRS1.

From the critical density of the H$^{13}$CO$^+$ J=1−0 transition (Evans 1999), the mean H$_2$ densities of the dense clumps are estimated to be more than $10^5$ cm$^{-3}$. The free full time of these clumps is less than 10$^5$ yr, and comparable to the time scale of cavity formation. These clumps in the dense shell may now be on the verge of forming stars. Thus, within a timescale of 10$^5$ yr, the formation of stars in the NGC 2264 IRS1 region is not necessarily a coeval process. MMS4 and 5 appear to be in an earlier stage of evolution than IRS1 (W00). It is therefore reasonable to suppose that the dense clumps are compressed by the ram pressure of the molecular outflow from IRS1 and will eventually form stars. Although further interferometric observations are required to determine the physical parameters of the outflow, it is reasonable to suggest that energetic outflows from intermediate-mass stars may act as a triggering agent for the birth of small clusters of low-mass stars in the vicinity.

7. Summary

High angular resolution interferometric observations and mapping observations using a single-dish telescope were performed for the region around the young intermediate-mass star, NGC 2264 IRS1. The continuum map reveals four sources, three of which correspond to submillimeter sources without bipolar outflow. Four compact clumps are also detected in the H$^{13}$CO$^+$ map, two of which are associated with these millimeter/submillimeter continuum sources. These H$^{13}$CO$^+$ clumps form an incomplete dense shell of 0.12 pc in diameter around IRS1.
No. | Dense Shell around a Young Intermediate-Mass Star NGC 2264 IRS1

Fig. 7. Schematic of the NGC 2264 IRS1 region

The outer part of the shell is well traced on the single-dish map. The presence of a shell or cavity structure suggests that the outflow from IRS1 has dispersed part of the surrounding envelope over ∼ 0.1 Myr. The kinematic properties can be interpreted as indicating two clumps of entrained or compressed material formed the steady outflow.

Figure 7 shows a schematic of the configuration of the H^{13}CO^+ clumps, the molecular outflow, and a group of pre-main sequence stars around IRS1. This group of YSOs including IRS1 is enclosed by an H^{13}CO^+ dense shell in the molecular cloud core detected by the single-dish observations. Three compact H^{13}CO^+ clumps associated with the continuum sources are located at the inner edge of the dense shell. These clumps may represent future sites of formation of a group of low-mass stars. The action of the outflow from IRS1 may have created the shell structure around IRS1, and may now be compressing the clumps and inducing star formation.

The authors are grateful to the staff of the Nobeyama Radio Observatory, D. Malin for providing the unsharp-masked image of NGC 2264, and K. Ogura for reading the manuscript and providing helpful comments.

References

Evans, N.J.H 1999, ARA&A, 37, 311
Nakano, M., Yamauchi, S., Sugitani, K., & Ogura, K. 2000, PASJ, 52, 437