THE ORION STAR-FORMING COMPLEX

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ABSTRACT. High resolution images of the Orion Nebula in the millimeter wave emission lines of CS and CO taken with the 45-m telescope at Nobeyama are presented. They cover a field approximately 400" square with a 15" - 34" resolution and reveal a wealth of information on kinematic and density structures. The images of the J=1-0 (49 GHz) and J=2-1 (98 GHz) lines of CS show a long (>1 pc) and narrow (∿0.1 pc) N-S ridge of dense molecular gas. On the ridge, two major clumps are recognized; one is associated with the KL object and the other is 100" south of it. The images of the J=1-0 (115 GHz) CO line indicate interaction between the molecular cloud and the H II region formed by the Trapezium stars. Bright CO emission is found towards the edges of the denser part of the H II region delineated by radio continuum emission. The CO emission coincides with the emission of vibrationally excited H_2 and the 3.3 μm dust emission feature. The CO images reveal filamentary structures ("streamers") stretching radially from the KL region. On the streamers there are Herbig-Haro objects moving away from the KL region. They may be tracers of weak interaction between the ambient molecular gas and mostly unseen, highly collimated, high-velocity (>200 km/s) jets.

1. INTRODUCTION

From the very early days of research on star formation, the Orion Nebula has been the most observed star forming region and probably the one that has provided the richest information on the subject. This is also true for the last ten years of research. In particular new infrared and radio techniques have revealed a detailed picture of a forming star embedded in the central part of the Orion molecular cloud.

The current picture of this region is briefly outlined as follows (Hasegawa 1986 and references therein). In the Kleinmann-Low infrared nebula is an obscured compact infrared source named IRc2. It has an enormous luminosity of 10^5 $L_\odot$ and is supposed to be a massive (∿50 $M_\odot$) protostar. High-velocity molecular outflow at velocities up to ∿100

M. Peimbert and J. Jugaku (eds.), Star Forming Regions, 123–137.

https://doi.org/10.1017/S0074180900095115 Published online by Cambridge University Press

km/s is observed from a very compact (∿30" in diameter) area surrounding the KL nebula. A part of the gas exhibits the characteristics of a bipolar outflow probably produced by IRc2. The dynamical interaction between the outflow and the ambient molecular gas excites strong shocks, which is evidenced by intense emission of infrared spectral lines from vibrationally excited H_2. Surrounding the protostar is an expanding ring of dense molecular gas 20"-30" in diameter. The expanding ring is encircled by a larger (>80" in diameter) disk of molecular gas rotating differentially. The molecular disk is centered on IRc2 and its axis coincides with the direction of the bipolar outflow. The structure and the kinematics of the molecular gas in the vicinity of IRc2 as a whole show a highly axisymmetric and bipolar nature.

How does this bipolar flow-plus-disk geometry around the protostar fit into the larger scale structure of the molecular cloud? The answer to this question could give us a clue to the origin of the bipolarity. It is also important to assess the effects of the interacting H II region on the star formation occurring in this region and the influence of the protostellar activities to the surrounding molecular cloud.

In this paper we present a new set of images of the CS J=1-0 (48.991 GHz), CS J=2-1 (97.981 GHz), and CO J=1-0 (115.271 GHz) emission taken with the 45-m telescope of the Nobeyama Radio Observatory. The data were taken on a grid spaced by 15" and the sizes of the beams (HPBW) are 34" (49 GHz), 18" (98 GHz), and 15" (115 GHz). About 800 positions in each image were observed to cover an area 400" square; the images are large enough to reveal even global structures of the core of the Orion molecular cloud with the highest spatial resolution ever achieved with single-dish observations.

2. CS IMAGES --- DENSE MOLECULAR GAS

2.1. The Molecular Ridge

Figure 1 shows the images of the CS J=1-0 and J=2-1 emission integrated over V(lsr) = 5 - 15 km/s. The images of the 400 μm continuum emission from warm dust (Keene, Hildebrand, and Whitcomb 1982) and the 6 cm continuum emission from the H II region (Johnston *et al*. 1983) are also shown for comparison. Positions are expressed as R.A. and decl. offsets in arcsecs from IRc2: R.A. = 5h32m46.9s decl = -5°24'23" (1950.0).

The dense ($n(H_2) > 10^4$ cm^{-3}) molecular gas sampled by the CS emission is distributed as a long, narrow ridge extending north-south called the molecular ridge (e.g., Liszt and Linke 1975). The whole length of the ridge is more than 440" which corresponds to 1.1 pc at a distance of 500 pc. The width of the ridge is roughly 40" (FWHM) or 0.1 pc in E-W direction, consistent with the estimate by Goldsmith *et al*. (1980) based on their observations of the J=3-2 and J=2-1 lines of CS. The overall appearance is similar to the images of the (1,1) and (2,2) line emission of NH_3 with 43" resolution presented by Batrla *et al*. (1983). The CS emission shows a striking resemblance to the 400 μm continuum emission which is a good measure of the column density of warm

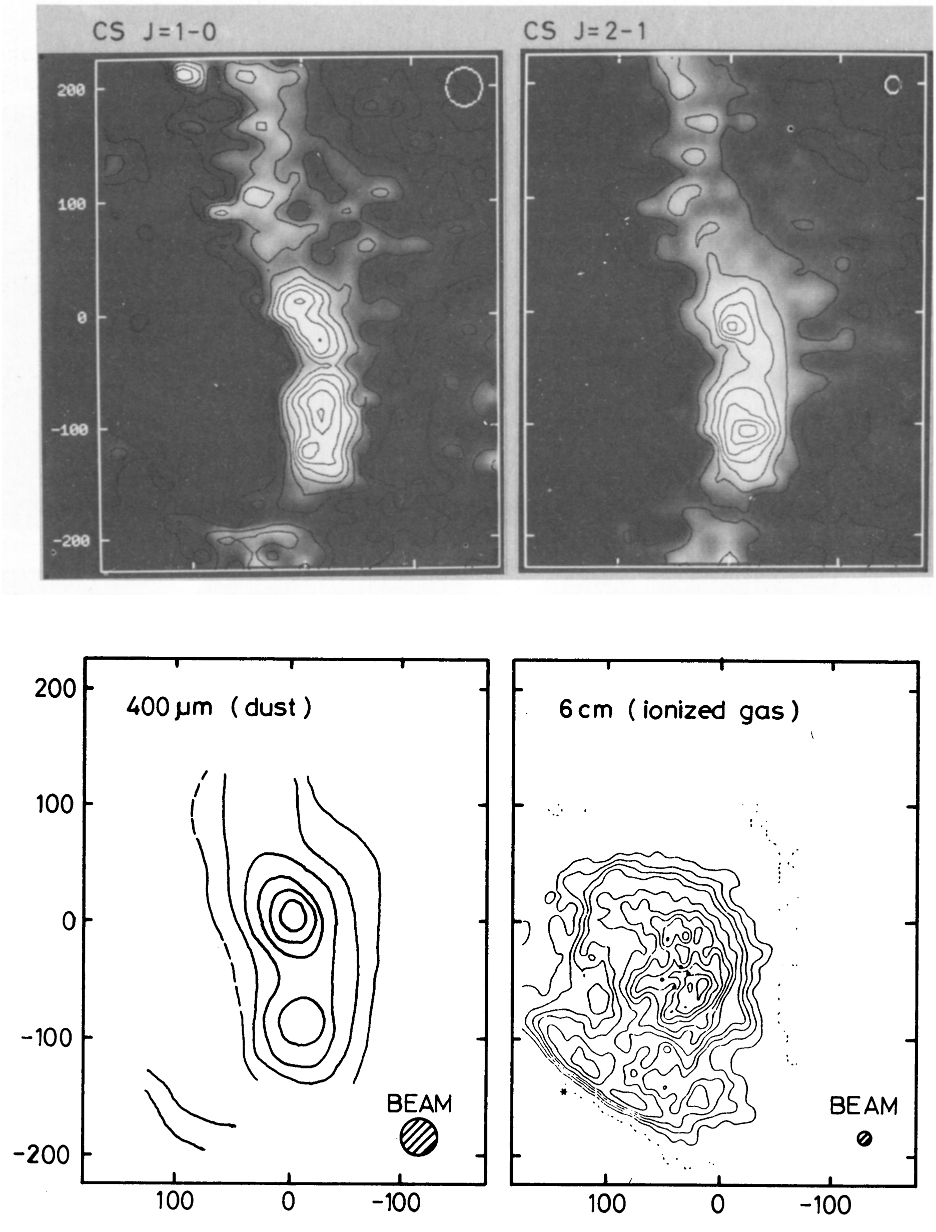

Figure 1. (upper panels) Images of the Orion Molecular Cloud in the J=1-0 and J=2-1 lines of CS. Positions are expressed as offsets in R.A. and decl in arcsec from IRc2: R.A. = 5h32m46.9s, decl = -5°24'23" (1950.0). Beam sizes are indicated in the upper right hand corners of the panels. (lower left) The image of the 400 μm emission from dust taken from Keene, Hildebrand, and Whitcomb (1982). (lower right) The image of the 6 cm continuum emission due to ionized gas taken from Johnston et al. (1983).

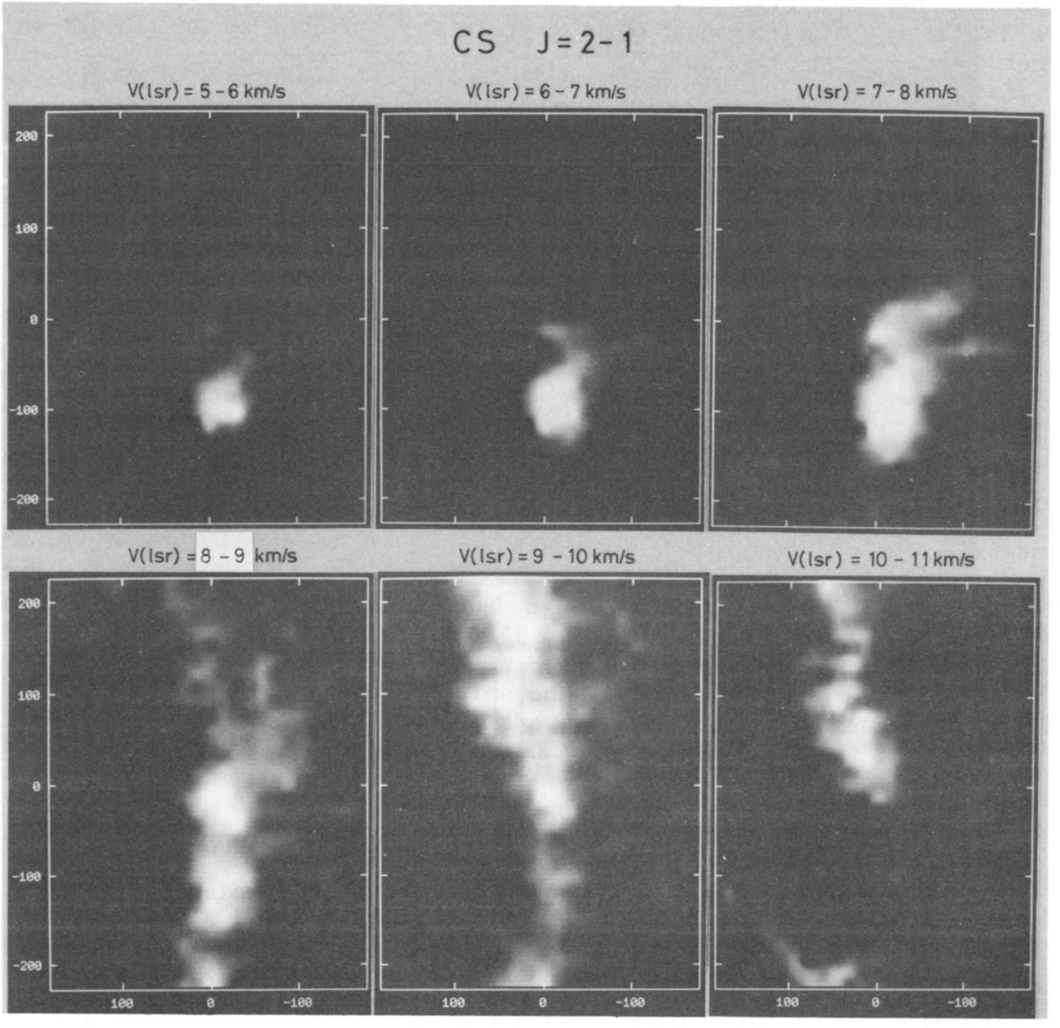

Figure 2. Images of the J=2-1 emission of CS at every 1 km/s of the radial velocity, V(lsr). Positions are offsets in arcsec from IRc2.

($T_d \sim 60$ K) dust. This may suggest that the CS emission reflects well the column density of the molecular gas unless there is a large change in the dust-to-gas ratio and/or the dust temperature in a large scale.

Two major clumps are readily noticed along the ridge; one is associated with the KL object near (0",0") and the other is 100" south of it. Smaller and less prominent clumps may be recognized in the northern part of the ridge.

https://doi.org/10.1017/S0074180900095115 Published online by Cambridge University Press

2.2. Kinematical Structure of the Molecular Ridge

Figure 2 shows images of the CS J=2-1 emission at a series of radial velocities, V(lsr), spaced by 1 km/s. At velocities lower than 9 km/s the emission is mainly from the southern half of the ridge, while the northern half is brighter at velocities higher than 9 km/s. This tendency is readily visible on the position vs. velocity diagram along the ridge shown in Figure 3. The southern half of the molecular ridge shows a considerable change in velocity with the large clump 100" south of KL being at the lowest velocity, 7 km/s. In the northern half, on the other hand, the highest velocity occurs close to KL and declines smoothly northward, approaching the mean velocity of this region, 9 km/s. There appears a jump in velocity at the center, i.e., the position of IRc2. The velocity field of the rotating dense molecular disk surrounding IRc2 is smoothly connected to the kinematical structure of the molecular ridge.

What has caused the velocity change along the molecular ridge? One possible hypothesis is that it is due to a global rotation of the molecular cloud (e.g., Liszt et al. 1974; Evans et al. 1975). A large scale velocity gradient is recognized over some 70 pc in the southern extension of the giant molecular cloud complex (Kutner et al. 1977) and it is plausible that the angular velocity has increased during fragmentation and collapse to form the dense ridge near the KL object (Linke and Wannier 1974; Kutner, Evans, and Tucker 1976).

Another possibility is that the southern part of the ridge has been driven to blueshifted velocities by the interaction with the expanding H II region. As seen in Figure 1, the ridge runs just on the western side of the dense H II region. The two major clumps noted above are coincident with steep falloffs of the 6 cm continuum emission at only 60" (projected distance of 0.15 pc) from θ^1C, the most luminous member of the Trapezium cluster. The blueshifted velocity found only at positions where the molecular cloud is in contact with the ionization front suggests a dynamical interaction between the molecular cloud and the expanding H II region (Figures 2 and 3). Evidence for such interaction is indeed found at the bright bar 110" or 0.27 pc southeast of Trapezium, where the molecular cloud is shocked and accelerated to a redshifted velocity (see Section 3.1). The 6 cm absorption line of H_2CO observed around the southern clump (Johnston et al. 1983) may indicate that at least some part of this clump is on the near side of the dense H II region, so that we can expect blueshifted velocities as a result of expansion of the H II region. The pressure from the H II region is estimated to be marginally sufficient to accelerate the southern clump by 1 km/s in 10^5 years. In view of a number of observed characteristics explained coherently, we consider more plausible the latter possibility that the large-scale velocity field in the molecular ridge is dominated by the dynamical interaction with the H II region, although we cannot rule out the first possibility of the amplification of the initial angular motion in a large scale.

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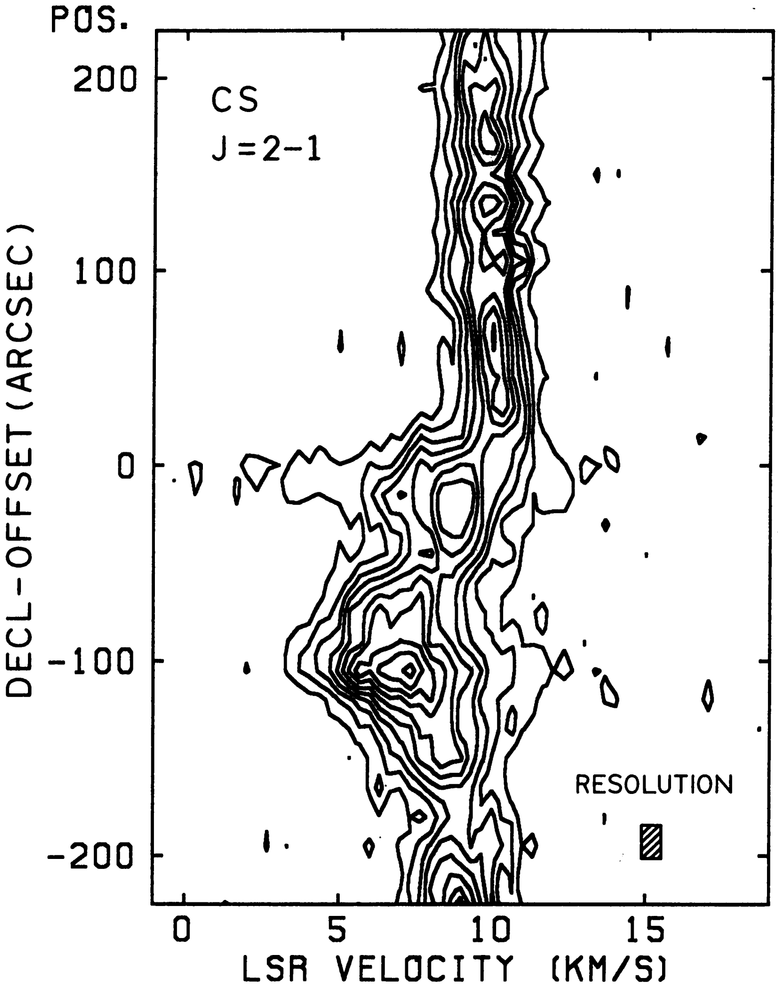

Figure 3. A position vs. velocity diagram of the CS J=2-1 line. The positions are taken along the molecular ridge shown in Figure 1 and are expressed as declination offsets from IRc2 in arcsec. Note the velocity shift at 0" (KL) and at -100". The velocity resolution is 0.75 km/s.

2.3. The Clumps of Dense Molecular Gas

The molecular ridge is not a smooth, continuous structure, but is composed of a chain of local peaks of the CS emission. As these peaks may correspond to local maxima of the gas column density, the ridge may be clumpy. Separations between clumps are in the range of 0.10 - 0.25 pc.

Previous observations of the CS and $C^{34}S$ J=1-0 emission in a limited area around IRc2 have suggested the existence of a rotating molecular disk 0.2 pc (80") in diameter (Hasegawa et al. 1984). A differential rotation of the molecular disk within 0.1 pc from the central protostar is observed (Vogel et al. 1985). The present observations show that this rotating motion fits well in the global kinematics of the molecular ridge displayed in Figures 2 and 3. The rotation curve drawn by Vogel et al. (1985) appears to be connected smoothly to the larger scale velocity law, especially toward the northern part of the ridge. This supports the possibility that the origin of the rotation of the disk was due to the local angular momentum generated by the dynamical interaction with the H II region.

The clump 100" south of the KL region has been observed in the 400 μm continuum emission (Keene, Hildebrand, and Whitcomb 1982) and in molecular lines (e.g., Batrla et al. 1983; Johnston et al. 1983; Bastien et al. 1985). The present observations reveal that this clump is very bright in the CS J=1-0 line emission as well as in the far infrared. Its mass can be estimated from the integrated intensity of the CS emission or the 400 μm flux density. In both cases the mass of the southern clump is comparable to or even larger than that of the rotating disk around the KL object, i.e., 100 - 300 $M_\odot$. Jaffe et al. (1984) suggested that these two clumps could form a binary system. From a projected distance between the two clumps, L = 0.24 pc, masses of the clumps, $M_1 = M_2 = 150\ M_\odot$, and their orbital velocity, $\Delta V = 1.3$ km/s, the kinetic and gravitational energies of the system are estimated as:

$$\text{(kinetic)} \qquad (M_1+M_2)\Delta V^2/2 = 0.5 \times 10^{47} \text{ erg,} \quad \text{and}$$

$$\text{(gravitational)} \qquad GM_1M_2/L = 8 \times 10^{47} \text{ erg.}$$

The kinetic energy above is a lower limit because the orbital motion is estimated only from its component in the line-of-sight, whereas the gravitational energy is an upper limit because a projected distance is used. In spite of these ambiguities, the gravitational energy exceeds the kinetic energy by a large factor and the system may be bound.

Close comparison of the J=1-0 and J=2-1 images of the clumps shows that the J=2-1 emission has sharp maxima towards the centers of the clumps, while the J=1-0 emission shows plateaus or even double-peaked structures in the clumps. This may be due to a density gradient in each clump, which may be flattened in a shape of a disk or a slab.

3. CO IMAGES --- EVIDENCE FOR INTERACTIONS

3.1. Interaction with the H II Region

In contrast to the CS lines, the CO J=1-0 line at 115 GHz is excited in less dense molecular gas and is optically thick in most cases, being a probe of the structure and kinematics of molecular gas heated by the interaction with the H II region. Figure 4 shows the images of the CO line emission taken with the 45-m telescope in comparison with the

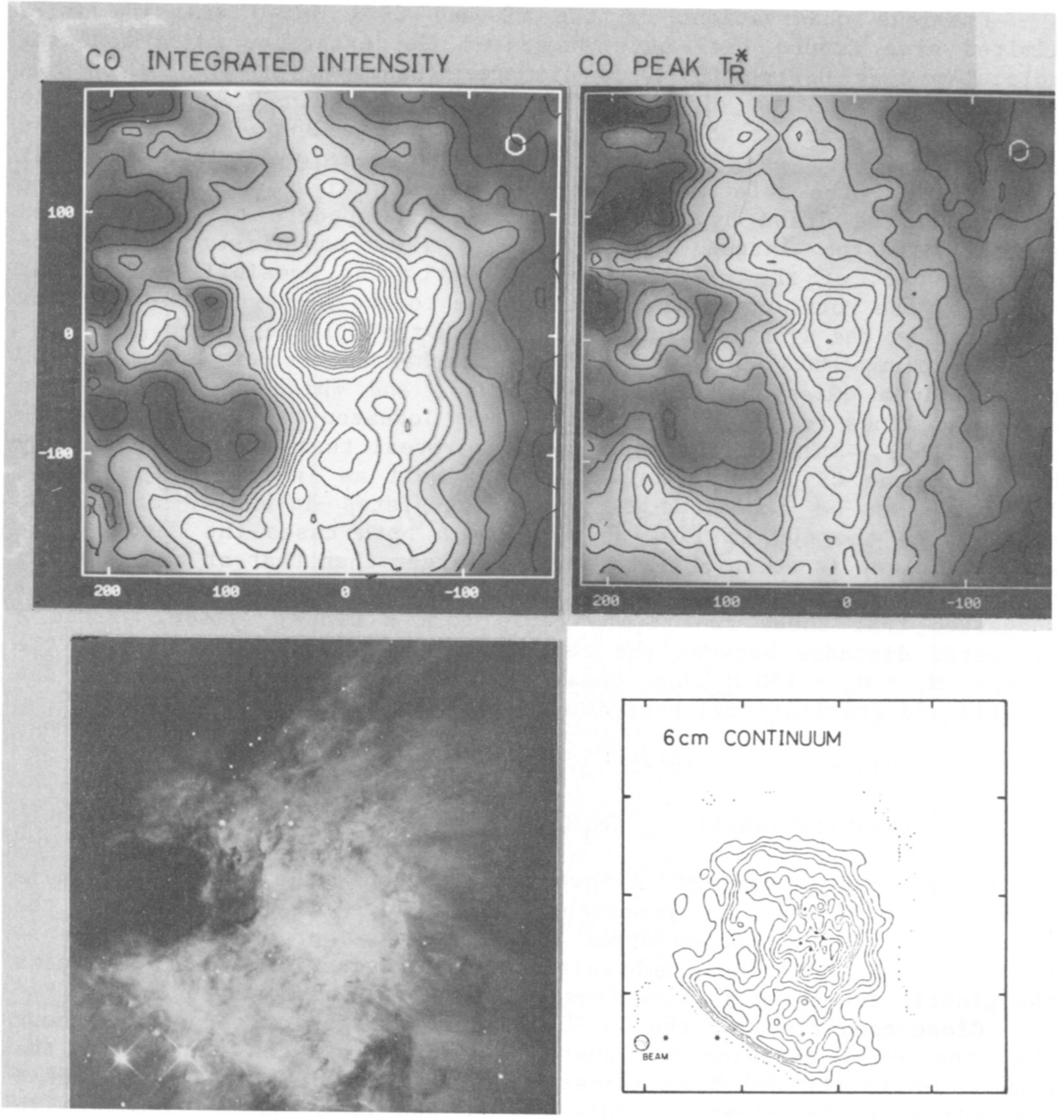

Figure 4. (upper panels) Images of the Orion Molecular Cloud in the CO J=1-0 line emission. In the image of the integrated intensity shown in the left panel, the broad emission in the KL region appears as a bright peak at the center, while the image of the peak antenna temperature in the right panel shows ridges of bright CO emission at interfaces between the molecular cloud and the H II region. Each frame covers approximately the same area as the ones in Figure 1 and the positions are expressed as R.A. and decl offsets from IRc2 in arcsec.
(lower panels) The optical and radio images of the H II region. The radio image was taken from Johnston et al. (1983).

https://doi.org/10.1017/S0074180900095115 Published online by Cambridge University Press

images of visible light and radio continuum emission. Along with the N-S ridge apparent in the CS images, two straight ridges are noticed in the CO images especially of the peak T_R*; one runs from (R.A.-offset, decl-offset) = (50", 60") to (200", 70") along the northern rim of the region of radio continuum emission and further, and the other runs along the bright bar ionization front visible in the SE corners of the optical and radio continuum images in Figure 4. These two and the bright southern half of the N-S ridge as a whole appear to surround the region of bright optical and radio continuum emission.

A series of CO images at every 1 km/s in radial velocity shown in Figure 5 reveals the velocity structure of the molecular gas in the vicinity of the ionization fronts. The ridge of CO emission associated with the bright bar appears most prominent at V(lsr) = 10 - 11 km/s, redshifted by 2 km/s relative to the main body of the molecular cloud. This suggests a dynamical interaction between the ionized and molecular gas (Schloerb, Goldsmith, and Scoville 1982; Schloerb and Loren 1982; Omodaka, Hayashi, and Hasegawa 1984; Sugitani et al. 1986), which excites the shock observed in rotation-vibration lines of H_2 (Hayashi et al. 1985). The detailed structure of the H II-molecular interface along the bright bar is discussed by Omodaka et al. (1987).

The global geometry of the bright CO emission is quite similar to that of the extended H_2 line emission and the 3.3 μm emission feature (Gatley and Kaifu 1987). The H_2 emission originates either in shocks driven by the H II region or at the cloud surface exposed to soft ultraviolet radiation field. The case of the bright bar suggests that the variation of the emission from the latter mechanism (i.e., fluorescence) is smooth over the Orion Nebula, so that the close resemblance between CO and H_2 may indicate shocks in the region of bright CO emission (Tielens and Hollenbach 1985).

3.2. "CO Streamers": Interaction with the High Velocity Flow?

The high velocity outflow of the molecular gas from the KL region was first noticed as broad wings in the CO line profiles, which result in the peaked maximum toward the center of the image of the integrated intensity in Figure 4. Subsequent observations with higher resolution have resolved the bipolar structure of the outflow which appears to be confined to a very small area 30" (FWHM) in diameter. The H_2 emission in two bright spots just outside this area originates in shocks excited by the dynamical interaction between the high velocity flow and the quiescent molecular gas.

The new CO images presented in this paper suggest another aspect of the interaction between the outflow and the ambient molecular gas. The frames of V(lsr) = 6 - 7 and 7 - 8 km/s in Figure 5 show a straight feature extending northward from the KL region; it can be traced from (0", 50") north of KL to (50", 150") and farther. Another feature reaches out to the west at V(lsr) = 10 - 11, 11 - 12, and 12 - 13 km/s; it runs from the bright KL region through (-100", 80") to the edge of the field of view. Although the CO images show signs of scanning effects, i.e., small calibration errors apparent as darker or brighter lines in the images, the straight features noted above run across them

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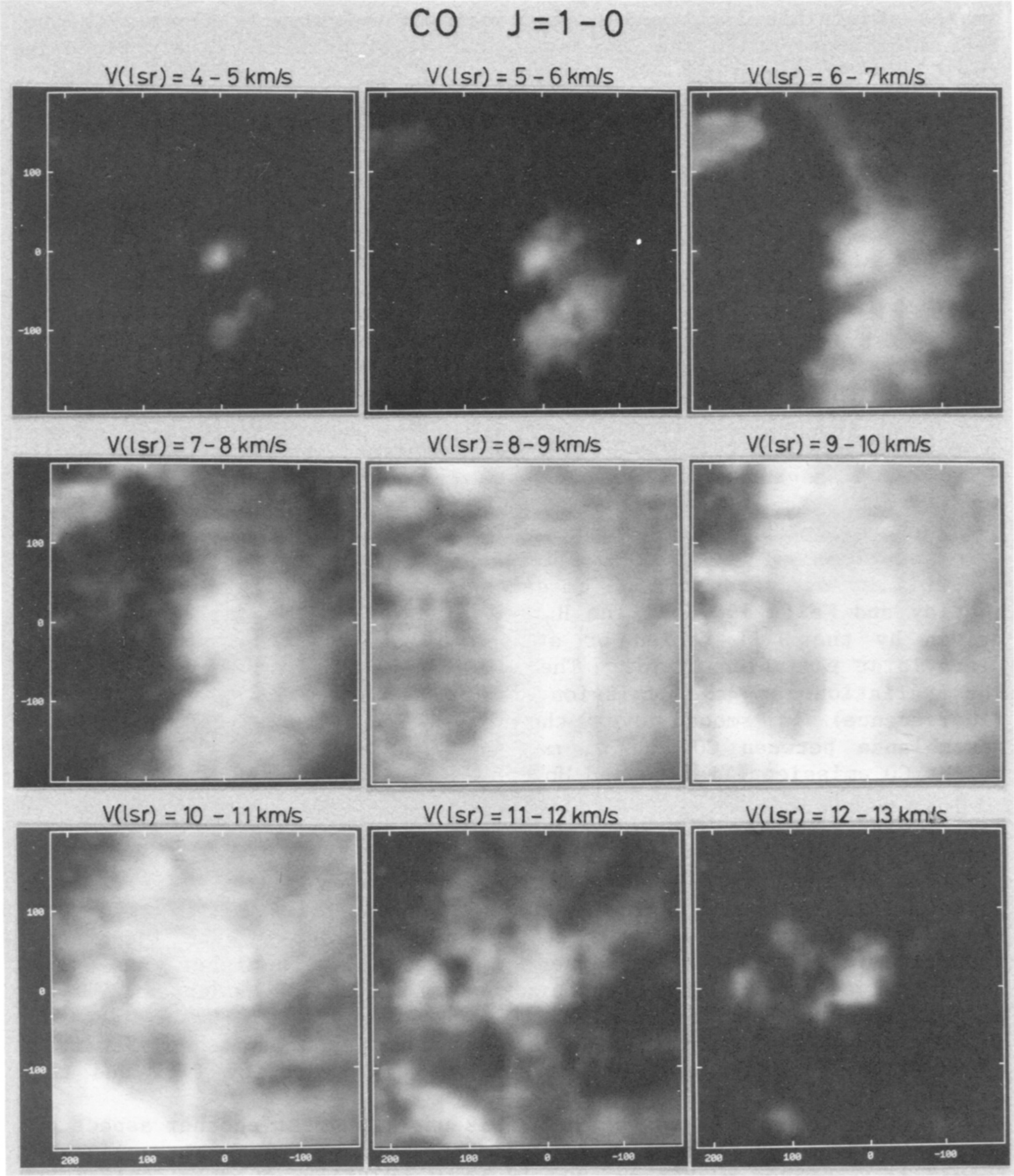

Figure 5. Images of the CO J=1-0 emission at every 1 km/s of radial velocity, V(lsr). Positions are offsets in arcsec from IRc2.

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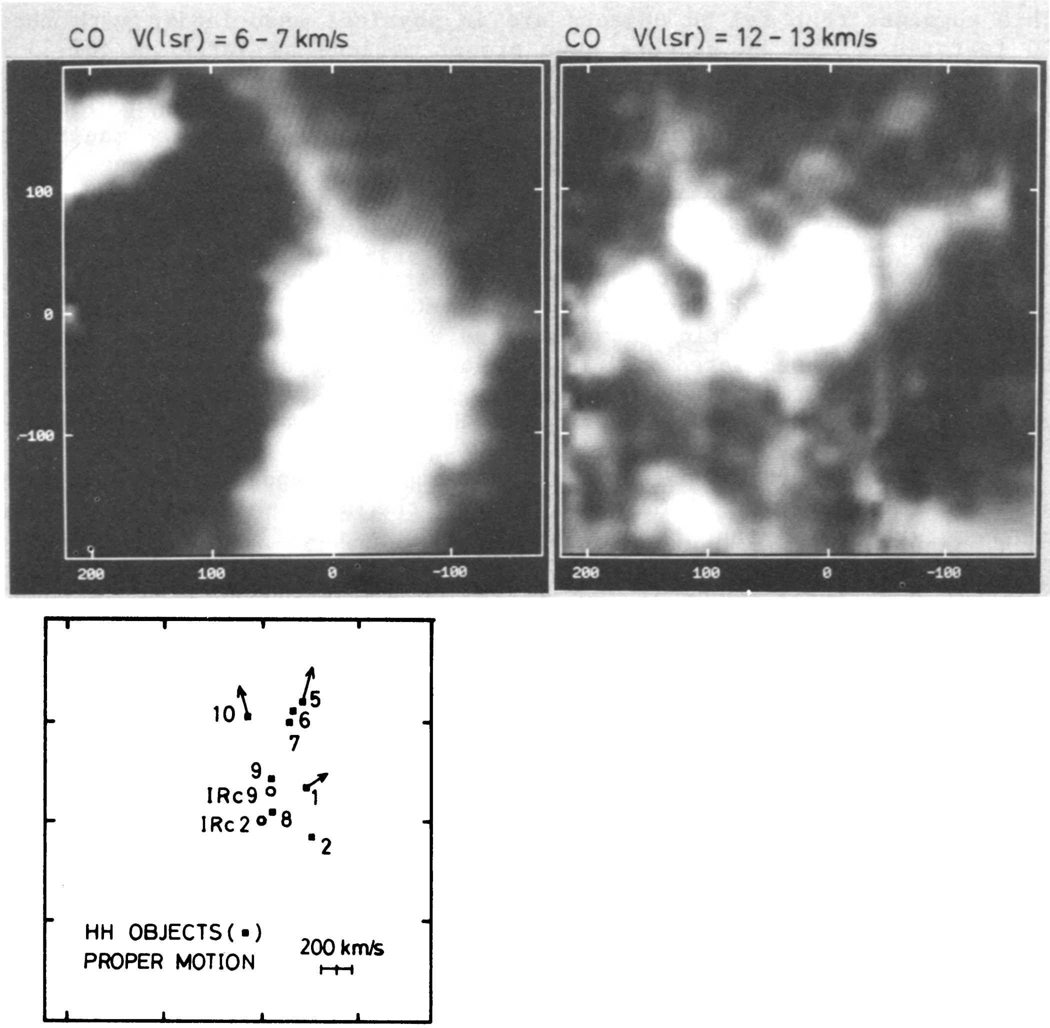

Figure 6. (upper panels) Straight CO features ("streamers") extending from the KL region. Weaker emission is stressed compared to the corresponding frames in Figure 5. (lower panel) Positions and proper motions (if available) of the Herbig-Haro objects around the KL object taken from Jones and Walker (1985).

and cannot be spurious. In the CO line profiles, these features appear as a low velocity wing or a shoulder.

Figure 6 shows the features at two representative velocities along with positions of the Herbig-Haro (HH) objects and their proper motions indicated by vectors on objects 1, 5, and 10 (Jones and Walker 1985). HH objects 9 and 10 are found on the northern CO feature while HH object 1 is on the western feature. Moreover, HH objects 1 and 10 have proper motions exactly in the directions along the lengths of the CO features.

This suggests that the HH objects are in physical association with the CO features. The HH objects have proper motions as large as 167-236 km/s of tangential velocity and their optical spectral lines show blueshifted wings extending to -250 km/s or further in radial velocity (e.g., Münch 1977). This suggests that the HH objects manifest outflows at a very high velocity (Axon and Taylor 1984). Finger-like filaments of H_2 v=1-0 S(1) emission extending from the KL region are observed, which indicates shock dissipation of the energy of the high-velocity flow (Taylor et al. 1984). In the region of H_2 filaments, a spatially narrow ridge of moderately broad ($\Delta V \sim 40$ km/s) emission has been discovered in the HCO^+ J=1-0 line, which is interpreted as originating from shocked gas (Olofsson et al. 1982). The CO features associated with the HH objects may be another evidence of interaction between the high-velocity flow and the ambient molecular gas. These features observed in H_2, HCO^+, and/or CO may be called "streamers".

It is noteworthy that the CO streamers extend far beyond the associated HH objects. This means that the high velocity flow has reached farther and that the HH objects are in the flow; they are not tips of jets leaving high velocity tails behind. The streamers are brighter near their roots in the KL region and get weaker at farther positions along their lengths. This suggests that the energy supply from the high-velocity flow to the streamers is continuous in their dynamical timescale of $\sim 10^3$ years. This is especially true for the H_2 streamers because the cooling time for the shocked H_2 is of the order of only 3 years. The strength of the interaction and the energy dissipation rate may be different from one streamer to another because the two streamers seen in CO are not bright in H_2 while the ones with brighter H_2 emission are not obvious in CO.

These observations seem to point to the following picture of the large high-velocity flow in this region: Well outside the region of the high-velocity molecular emission confined within a small area 30" in diameter, there exist flows of energy most probably in a form of atomic or ionized gas moving at velocities as high as 300 km/s. The flows reaching out to >150" (0.37 pc) from the KL region interact with the ambient molecular gas and become visible. Stronger interaction excites shocks, which are observed as HH objects and H_2 streamers. Weaker interaction produces CO streamers. Each of the streamers may trace a well-collimated high-velocity jet. The mechanism to form many collimated jets is unknown.

The discovery of the mostly unseen jets of high-velocity gas forces us to reconsider their importance as an energy input to the quiescent molecular cloud. In the present case, the influence range by the flow is to be revised upward by a factor of 5 or more compared with the extent of the molecular flow. Attempts to estimate the thermal and kinetic energies supplied to the molecular cloud by the jets are being made.

4. CONCLUSIONS

The high-resolution images of millimeter molecular lines taken with the 45-m telescope at Nobeyama are presented and compared with optical, infrared, and interferometric radio images. Various aspects of the activities associated with star formation are revealed:

1. The molecular ridge contains several clumps. Two major clumps are on the ionization front. One of which is a rotating disk surrounding IRc2, a protostar in the KL infrared nebula. The other is comparable to, or even larger than, the the clump around the KL nebula in size and mass.

2. There is dynamical interaction between the molecular cloud and the H II region. It may have accelerated a part of the molecular ridge. It also excites shocks at the interface between the molecular cloud and the H II region.

3. "Streamers" are stretching radially from the KL region. They run far beyond the boundary of the molecular high-velocity flow and are accompanied by HH objects. They may manifest mostly unseen high-velocity flows driven by the activity of young stellar object(s) in this region.

Acknowledgements.
The author wishes to thank his collaborators Ian Gatley, Norio Kaifu, Masahiko Hayashi, and Toshihiro Omodaka. This work was made under the United Kingdom - Japanese collaboration supported by the Japanese Ministry of Education and the SERC of the United Kingdom.

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SARGENT: With reference to your suggestion that KL and the southern Orion source may be a binary forming, I should like to report that Mundy and Scoville at Owens Valley have made CS observations at 7" of a 2'×3' region of that bridge. In fact, they find four condensations stretched along the ridge -each quite separate, of mass ∿ 50 $M_\odot$ and on the point of forming stars.

HASEGAWA: I agree they are strung out like a necklace.

HOLLENBACH: Theoretical models by Tielens and myself confirm the interpretation that the peaks in the CO (1-0), the strong 3.28 emission, and the *extended* (not BN-KL) H_2 emission come from the "photodissociation region", that is the interface region between the H II region and the molecular cloud. The H_2 emission is UV-pumped, not shock excited, in this interpretation.

WILSON: The absorption of the 6-cm line of H_2CO found by Johnston *et al.*

indicates that this molecular cloud may be *inside* the H II region (see A & A 138, 225). Thus, this may be a Partially Ionized Globule (PIG).

HASEGAWA: I agree.

TAKANO: I would like to give a comment on the "streamers". The CO streamers in Orion are much more extended structures than the CO high velocity flow which can be seen just around IRc2. We have also found an extended NH_3 streaming cloud in the HH7-11 region with the Effelsberg 100-m telescope. The NH_3 streaming cloud is elongated in the direction of HH7-11 and HH5, and has a low blue-shifted velocity of 1-2 km s^{-1} relative to the dense central cloud surrounding the central infrared source SSV13 (see Takano *et al.* elsewhere in this book). Sandell and Liseau found that the CO blue-shifted high velocity flow is abruptly stopped around HH7. Recently, we have detected 2 μm H_2 molecular emission around HH5 with a tail structure in the direction toward SSV13 as well as a well-collimated bipolar lobe around SSV13. Therefore, we conclude that the NH_3 streaming cloud is also expelled matter from the central part of the cloud around SSV13 at low velocity. If this is the case, the time-scale of this streaming cloud is 50 times longer than the value derived from the CO high velocity flow data. Therefore, I believe that some bipolar flow objects have a low velocity, extremely extended streaming cloud as well as a high velocity CO flow.

FUKUI: The CS maps (1-0) (2-1) have an elongation which lies just toward the western edge of the H II region which is mapped in the radio continuum radiation. Although you interpreted the motion of the cloud in terms of gravity, I feel it is also possible to interpret it in terms of the interaction with the i-s front driven by the trapezium stars. Have you ever thought about this possibility?

HASEGAWA: Yes. It is quite probable that the pressure of the H II region has given the momentum to the molecular cloud in its stage of collapse and fragmentation. That motion could have supplied the angular momentum of the disk now surrounding the KL object.