APERTURE SYNTHESIS OBSERVATIONS OF CS, NH_3, AND CONTINUUM IN THE BIPOLAR FLOW SOURCE NGC2071-IRS

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ABSTRACT. We have made aperture synthesis observations of CS(J=1-0, 2-1) and NH_3(1,1) lines and 49, 98, and 110 GHz continuum in NGC2071-IRS with the Nobeyama Millimeter Array. We have obtained maps of these lines and continuum maps with 2".7-20" resolution. We have found that dense molecular gas has a disk structure with a radial scale ranging 0.01 pc - 0.1 pc and has a ring-like structure with expanding motion at the central 5000 AU region. We also have found that there exists double dust continuum sources which are separated by 2500 AU in projection and are apparently located at the inner edges of the ring. Our observational results suggest that the disk of molecular gas has a central hole formed by wind and UV radiation from a central young stellar object, the central part is expanding, and that dust continuum emission comes from tangential parts of the shock compressed ring ($r \sim 1300$ AU, $M(H_2) \sim$ 21-34 Mo, and $n(H_2) \sim 10^9$) at the most inner side of the disk structure. The other possible model of the dust continuum sources is a binary system of self-luminous young stellar objects.

I. Introduction

NGC2071-IRS is a young stellar object (or objects) with $L_{IR} \sim 900$ Lo (Harvey et al. 1979) and a typical example of CO bipolar flow sources (Bally 1982, Snell et al. 1984). Elongated structure of dense molecular gas suggesting the existence of a large scale gaseous disk was found by single dish observations (Bally 1982, Takano et al. 1984, 1986). VLA 5 GHz observations (Snell and Bally 1986) revealed the exsistence of three compact HII regions, each of which is associated with each of 10 μm sources (Persson et al. 1981) and each of H_2O and OH masers (Sandel et al. 1984). From these coincidences, it was suggested that each of these sources may be a young stellar object (Snell and Bally 1986). Excess of 3 mm continuum emission was found (Scoville et al. 1986). The emission is associated with two of three HII regions, but not spatialy resolved. It has been unclear whether the 3 mm emission comes from dust or a HII region.

Investigating the structure of dense molecular gas and dust cloud very close to young stellar objects helps us to understand star formation in the molecular gas disk and the evolution of dense molecular gas. However, there has been a large gap of spatial resolutions between the VLA sub-arcsecond structure of compact HII regions and the 40"-2' structure of dense molecular gas. We have made 2."7-20" resolution observations of NGC2071-IRS with the Nobeyama Millimeter Array in NH_3 and CS lines and 49-110 GHz continuum. The observations revealed new structures of dense molecular gas and dust. The results and interpretations are presented.

II. Observations

We have made aperture synthesis observations of CS(J=1-0, 2-1) and NH_3(1,1) emission from NGC2071-IRS with the Nobeyama Millimeter Array (Ishiguro et al.

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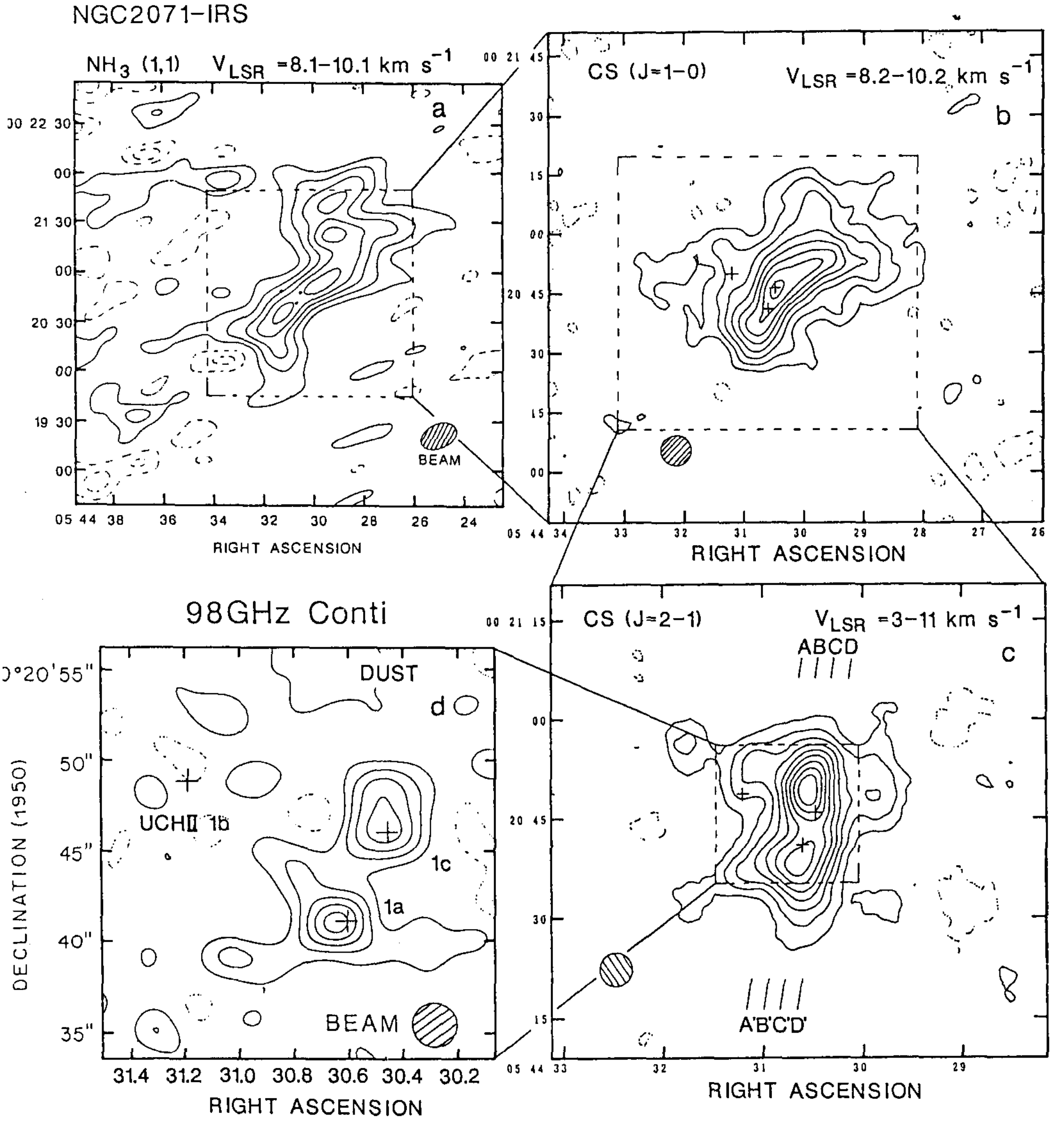

Figure 1. Montage of obtained maps of NH3(1,1), CS(1-0), CS(2-1), and 98 GHz continuum in NGC2071-IRS. Velocity ranges of the former three maps are V_{LSR}=8.1-10.1, 8.2-10.2, 3-11 km s^{-1}, respectively. Contour intervals are 88 mJy/beam, 144 mJy/beam, 165 mJy/beam, and 10.1 mJy/beam for the maps of NH3(1,1), CS(1-0), CS(2-1), and 98 GHz continuum, respectively. Three crosses (or dots) indicate ultracompact HII regions (1a-1c) in the VLA 5GHz map (Snell and Bally 1986), each of which corresponds to each of 10 um sources, IRS-1, 2, and 3 (Persson et al. 1981).

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1984, 1989) during Apr. 1987 to May 1989. We used HEMT receivers for 23.7 GHz (Kasuga et al. 1986) and dual frequency SIS receivers for 40/100 GHz (Kawabe et al. 1989). Their system noise temperatures (SSB) at the zenith were around 200 K (23.7GHz), 300 K (49GHz and 98GHz), and 500 K (110GHz). We used an FFT spectro-correlator (FX) with 1024 channels per baseline (Chikada et al. 1987). The bandwidths were 80 MHz for NH_3 and CS(1-0), and 320 MHz for CS(2-1) and 110 GHz continuum. Velocity resolutions were 1.0 km s^{-1} for NH_3 and CS(2-1), and 0.5 km s^{-1} for CS(1-0). Line free channels were used for mapping of continuum emission at 49, 98, and 110 GHz. The number of baselines and synthesized beam were 20, 60, 40, and 10, and 16"x23", 8", 5"(2.7" for 98 GHz continuum), and 7" for NH_3, CS(1-0), CS(2-1), and 110 GHz continuum, respectively.

III. Results

(i) Quiescent Component; Disk of Molecular Gas

Figure 1a and 1b show maps of intensities of NH_3 and CS(1-0) quiescent components integrated over narrow velocity ranges of V_{lsr} = 8.1-10.1, and 8.2-10.2 km s^{-1}, respectively. NH_3 emission was not detected outside this velocity range in our observations. The maps of NH_3 and CS(1-0) indicate flat, almost edge-on disk structures with sizes of 90"x<20" and 35"x10"(0.085 pc x 0.025 pc), respectively. The recent VLA result of NH_3(2,2) (Zhou et al. 1989) is very consistent with our NH_3 result. The disk structures are just perpendicular to the bipolar outflow (Snell et al. 1986, Scoville et al 1986) as already noted by Takano et al. (1984, 1986). Two of three compact HII regions associated with IRS-1 and IRS-3 are located at the center of the disk.

(ii) Wing Component; Expanding Ring inside the Disk

Figure 1c shows a map of the CS(2-1) intensity of an intermediate wing component (Kitamura et.al. 1989) integrated over a velocity range, V_{lsr} = 3-8 km s^{-1}. Wing component at higher velocity in CS(2-1) with an extent of 20 km s^{-1} has the same bipolarity as the CO high velocity flow (Bally 1982; Kitamura et al. 1989). The map indicate a more compact ridge than the NH3 and CS(1-0) disk, with a size of 20" x 10" (0.05pc x 0.025). The two peaks on the ridge are located outside two compact HII regions (i.e., VLA 5GHz sources, "1a" and "1c", associated with IRS-1 and IRS-3, respectively; Snell and Bally 1986). Figure 2 shows four position-velocity maps along four cuts (shown in Fig.1c) parallel to the ridge. A main feature in the maps is an oval pattern corresponding to a large non-circular motion (~4-5 km s^{-1}), which is traced with a dotted line in Fig 1c. This pattern and ridge structure suggest the existence of expanding molecular ring inside the disk. The dynamical center of the expansion is between two compact HII regions (see Fig. 2). Its expanding velocity and dynamical time scale are about 5 km s^{-1}, and 3×10^{3} years, respectively. The time scale is shorter than the dynamical age of the high velocity CO outflow, 1.6×10^4 years (Snell et al. 1986) by a factor of five. Such an expanding motion of dense molecular gas in the inner part of the disk was detected so far in Orion-KL (Plambeck et al. 1982) and GL490 (Kawabe et al. 1984).

(iii) 3 mm continuum; double dust continuum sources

Obtained total flux densities of contionuum emission at 49, 98, and 110 GHz are plotted in Figure 3 with other data (see Dent et al. 1989). The cm to mm spectrum of the continuum emission from NGC2071-IRS indicates that the 98 and 110 GHz emission almost comes from dust. The flux density at 49 GHz is explained well as a combination of free-free emission and dust emission.

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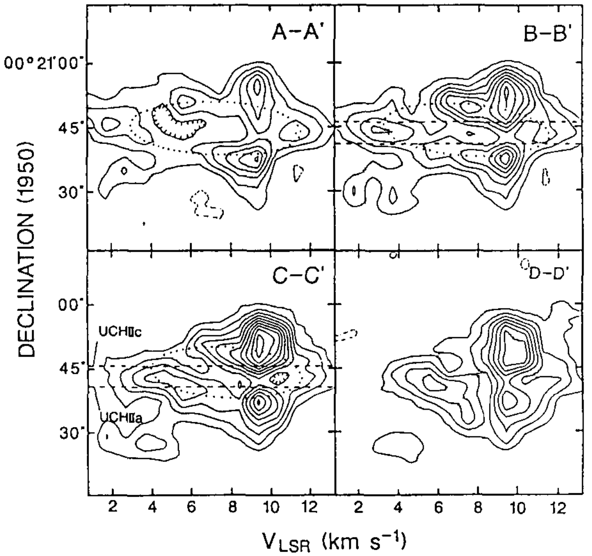

Figure 2. Four position-velocity diagrams in CS(2-1) along four cuts shown in Fig.1. Dotted line indicates a oval pattern of an expanding ring. Dashed lines indicate positions of two ultracompact HII regions.

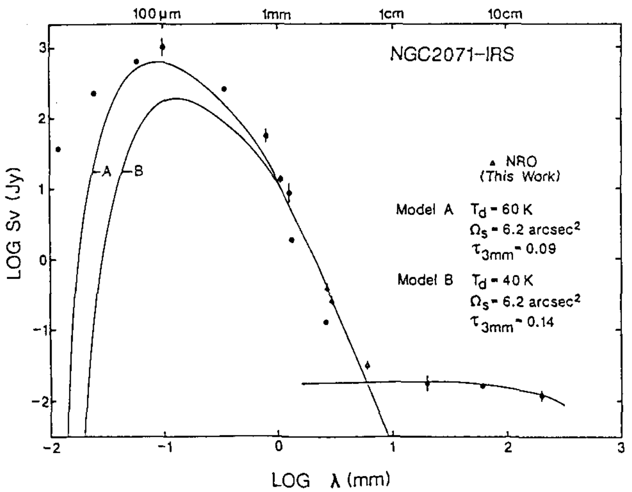

Figure 3. Spectrum of contimuum emission in NGC2071-IRS. Our data at 110, 98, and 49 GHz (△) are plotted with other data (see Dent et al. 1989).

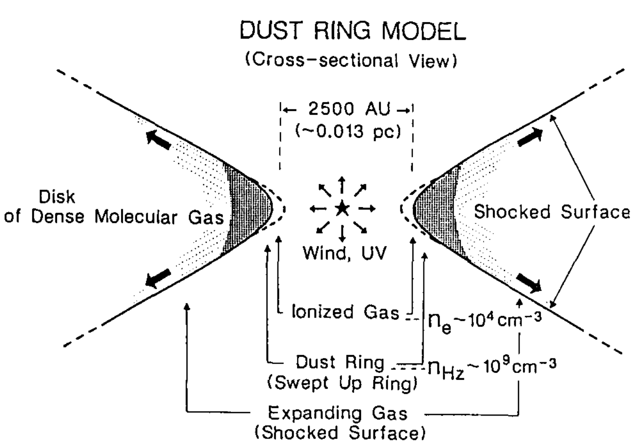

Figure 4. Schematic diagram of a dust ring model (cross-sectional view).

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Figure 1d shows a map of 98 GHz continuum emission. The emission is resolved to double point-like sources, each position of which coincides with each of the two compact HII regions (associated with IRS-1 and IRS-3). The two peaks at 98 GHz fall between the two CS(2-1) peaks. The CS(2-1) peaks and the 98 GHz point-like sources are aligned with the disk structure of the NH_3 and CS(1-0) emission.

We have fitted an uniform temperature model of the dust source to the spectrum in order to estimate a dust temperature, T_d, and a dust opacity at 3 mm, τ_{3mm}. We assumed a dust emissivity index of two and the source size in total, 6.2 arcsec^2, which is roughly estimated from the 98 GHz map (Fig. 1d). Fitting was done for fitted lines not to exceed over the lower envelope of single dish data at $\lambda < 1.3$ mm, because the data sample extended emission missed in our interferometric data. The dust temperature is estimated to be lower than ~60 K. Total mass and number density of H_2 molecule of the two sources are derived to be ~21-34 Mo and ~10^9 cm^{-3}, respectively, assuming T_d = 40-60 K (lower boundary, 40 K, is taken based on Takano 1986), an empirical relation between an H_2 column density and a dust opacity (Hildebrand 1983), and assuming that an extent of the dust sources along the line of sight is about 1200 AU.

IV. Models of Double Dust Continuum Sources

We have found two dust continuum sources with high H_2 density and large H_2 mass at the center of the disk and "expanding ring" of dense molecular gas ($n(H_2) \sim 10^4$-10^6 cm^{-3}). There are two possible model to explain the structure; one is a dust ring model and the other is a binary model of self-luminous young stellar objects.

(i) A Dust Ring Model

The positional relations between the double dust sources and the two CS(2-1) peaks suggest that the dust emission is strong at the tangential parts of the dust ring most inside of expanding ring and disk. A schematic diagram of this model is shown in Figure 4. The formation of the dust ring is explained as follows. The strong wind and UV radiation from a central newly formed star interact with high density gas in the disk region to form shock compressed ring in the equatorial plane, and accelerate the gas. The gas sweeping effect of shock raises the H2 mass of the ring according to the expansion of the ring. The expanding ring in the disk is an evidence of the interaction between the wind and the disk. The positional coincidence among HII regions, OH and H_2O masers, and dust continuum sources does not conflict with this model. Two HII regions and faint emission between them (Snell and Bally 1986) can be interpreted as an ionized inner edge of the dust ring. The masers would be excited at the inner edge. This ring model can produce the observed structures. A similar model to explain two 5 GHz continuum sources was also proposed for L1551-IRS5 (Rodrigues et al. 1987). The main argument against this model is that there is no observational evidence of single central driving source between IRS-1 and IRS-3.

(ii) A Binary Model

There is a possibility that each of the double dust continuum sources corresponds to a self-luminous young stellar object which is formed through fragmentation in the singel molecular gas disk. Simulations of isothermal rotationg clouds suggested that a flattened disk fragments and each of fragments has roughly equal mass, and that in total the flagments contain ~30%-40% of the cloud mass (Miyama et al. 1984).
The molecular gas disk in NGL2071 is very flat (see Fig.1). Each H_2 mass of binary dust clouds is almost equal and is estimated to be 10-15 Mo, and the dust clouds contains ~40%-80% of the total H_2 mass of the 30" region, because the 30" scale disk

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of molecular gas has a mass of 5-30 Mo (Takano et al. 1984). These properties of the disk and the double dust sources are roughly consistent with the results of the simulations. On the other hand, from positional coincidences of H_2O and OH masers, ultra compact HII regions , it was suggested that each of these sources may be a young stellar object (Snell and Bally 1986). These support the possibility of a binary. However, it is unclear which source drives the high velocity outflow and the "expanding ring", because each of two sources are shifted from the dynamical center of the "expanding ring" and the origin of the CO outflow (Scoville et al. 1986).

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Discussion:

SANDELL (Comment): I think you should review your interpretion of only one source carefully. The continuum appears to peak on the two free-free and IR sources. The discrepancy in spatial coincidence in CS may just be due to optical depth effects- the densities are extremely high. Polarization imaging or UKIRT with the infrared camera suggest that there is more than one source.

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