THE ASTROPHYSICAL JOURNAL, 282:L69–L71, 1984 July 15

HIGH ANGULAR RESOLUTION CS (J = 1–0) OBSERVATIONS OF THE BIPOLAR FLOW SOURCE NEAR NGC 2071: CAN THE CS COMPACT CLOUD COLLIMATE THE FLOW?

T. TAKANO, Y. FUKUI, H. OGAWA, H. TAKABA, R. KAWABE, Y. FUJIMOTO, K. SUGITANI, AND M. FUJIMOTO
Department of Astrophysics, Nagoya University
Received 1983 August 19; accepted 1984 April 19

ABSTRACT

We have observed the CO bipolar flow source near NGC 2071 in the J = 1–0 line of carbon monosulfide with 30″ resolution provided by the new 45 m Nobeyama telescope. We find a compact cloud with a size of $\sim$ 0.3 pc × 0.15 pc embedded in an extended cloud. This compact molecular cloud is more than 4 times smaller than was indicated in previously published coarser resolution observations, is elongated orthogonally to the bipolar flow, and shows strong signs of rotation. However, we estimate the mass of the compact cloud to be $\sim$ 10 $M_\odot$, much less than expected if it has been focusing the flow. We therefore conclude that collimation of the flow is taking place at considerably smaller scales unresolved with the 30″ beam.

Subject headings: infrared: sources — interstellar: molecules — nebulae: reflection — stars: formation

I. INTRODUCTION

NGC 2071 is a reflection nebula in the northern molecular complex in Orion. Near NGC 2071 lie infrared sources within a small region of $\sim$ 10″ extent (Persson *et al.* 1981) and a high-velocity CO bipolar flow was detected over a velocity range of 70 km s^{-1} around them (Lichten 1982; Bally 1982). Subsequently, molecular hydrogen emission was detected toward the infrared sources (Persson *et al.* 1981; Bally and Lane 1982).

Existence of a disklike structure with an extent of more than a few arc minutes elongated orthogonal to the direction of the high-velocity flow was claimed by Lichten (1982) and Bally (1982). However, their observational data are limited in spatial resolution. The beam sizes employed in their observations of 60″–100″ are not small enough to pick up detailed gas distribution near the infrared sources.

In this *Letter*, we report the CS J = 1–0 data of NGC 2071 obtained with a $\sim$ 30″ beam of the 45 m millimeter-wave telescope at Nobeyama. A more detailed account of the data as well as a comparison with GL 490 will be given elsewhere (Fukui *et al.* 1984).

II. OBSERVATIONS

Observations were made in 1983 January and April by using the new 45 m millimeter-wave telescope at Nobeyama[1]. The half-power beam width and the beam efficiency of the telescope were measured to be about 30″ and 0.65 by observing 3C 273. The pointing was accurate within 3″ in rms as determined by observing SiO maser sources at 43 GHz.

We used a cooled mixer receiver whose system noise temperature including the atmosphere was about 500 K (SSB) toward the zenith. The data were obtained with two acousto-optic spectrometers, each of which gave a velocity resolution of 0.24 km s^{-1} at 6 mm wavelength. The J = 1–0 lines of $C^{32}S$ (48.990964 GHz; Snell, Langer, and Frerking 1982) and $C^{34}S$ (48.206948 GHz) were observed simultaneously in the two spectrometers. The spectral intensity was calibrated by measuring an ambient temperature chopper wheel against the blank sky.

We mapped a region centered at R.A. = $5^h44^m30^s.0$ and decl. = 0°20′40″ (1950.0) which is close to the 10 μm emission peaks. Observations were made by position switching at 1 minute intervals to a reference position about 30′ away.

III. RESULTS

The CS profile toward the infrared sources is shown in Figure 1. The emission extends over $\sim$ 20 km s^{-1} having a main peak at $\sim$ 10 km s^{-1}, and there are subpeaks at $\sim$ 4, 16, and 19 km s^{-1}. These subpeaks have been detected only with the present high spatial resolution (see Fukui *et al.* 1984 for a further discussion). Maps of the integrated intensity for four velocity sections are shown in Figure 2. The emission at 8–12 km s^{-1} (Fig. 2*b*) is superposed on the CO bipolar flow in Figure 3. This is the main component of the CS spectra and appears elongated orthogonal to the direction of the bipolar flow. The size of the compact CS cloud is much smaller than that which is shown in the CS J = 2–1 map taken with a 100″ beam (Bally 1982). The 2–1 data show the CS cloud is distributed with an extent of $\gtrsim$ 4′. The present 1–0 data indicate that a much more compact component is actually embedded in the extended cloud that appears in the maps of CS (2–1) (Bally 1982) and NH_3 (Calamai, Felli, and Giardinelli 1982). It is noteworthy that there is still an indication of fine structures unresolved with the 30″ beam, in particular near the infrared sources.

The distribution of the CS high-velocity emission is shown in Figures 2*a* and 2*d*. The intense part ($T_A \geq 2$ K) of the blueshifted (2–8 km s^{-1}) and redshifted (16–22 km s^{-1}) emission are localized in the central region of 30″ radius. They show the same symmetry with the CO bipolar flow.

In Figure 4 we show a position-velocity diagram along the NW-SE direction. Near the infrared sources, the emission

[1]This work was carried out under the common use observation program at the Nobeyama Radio Observatory (NRO). NRO, a branch of the Tokyo Astronomical Observatory, University of Tokyo, is a cosmic radio observing facility open for outside users.

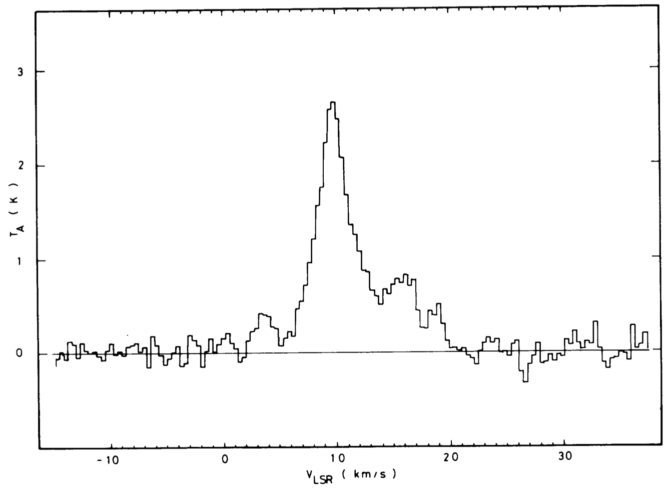

FIG. 1.—$C^{32}S$ J = 1–0 profile toward the infrared sources near NGC 2071 (R.A., decl. [1950.0] = (5^h 44^m 30ˢ0, 0° 20′ 40″). The profile is smoothed to 0.36 km s^{-1} velocity resolution.

extends significantly at $v \gtrsim 11$ km s^{-1} close to Δdecl. = 30″ and at $v \lesssim 10$ km s^{-1} close to Δdecl. = 0″. We identify this extended emission in velocity as lower velocity counterparts of the CS high-velocity components shown in Figures 2*a* and 2*b*. Within the CS compact cloud we see a strong velocity gradient of ~ 5 km s^{-1} pc^{-1}, while outside of it we do not see any sign of this strong velocity gradient; instead, we find some hints of weak velocity gradients in the opposite sense. This velocity gradient in the CS compact cloud is larger by about an order of magnitude than that suggested for the extended CS disk.

To summarize, the present data indicate the existence of a CS compact cloud around the infrared objects. The kinematics of this compact cloud appears to be independent of its ambient molecular gas.

IV. DISCUSSION

The spatial distribution of the CS main component and its velocity distribution strongly suggest the existence of a disk rotating around the symmetry axis of the CO bipolar flow. From the contour map in Figure 2 we estimate the radius of the disk to be ~ 0.15 pc and an upper limit for the thickness of the disk to be ~ 0.15 pc. If we designate the inclination angle of the disk to the line of sight as i, the rotation velocity at the edge of the disk and the rotation period are estimated to be 0.75/sin i km s^{-1}, and 1.3 × 10^6 sin i yr, respectively. The rotation velocity implies a dynamical mass within the disk to be ~ $20/\sin^2 i\ M_\odot$ if it is in dynamical equilibrium. On the other hand, if we take the mean densities of (3 × 10^4)–(2 × 10^5) cm^{-3} which were inferred from excitation considerations of molecular lines (Bally 1982), we obtain the molecular mass of 5–30 $M_\odot$ where we assume the thickness of the disk of 0.05 pc and uniform density. The total mass of the central stars is

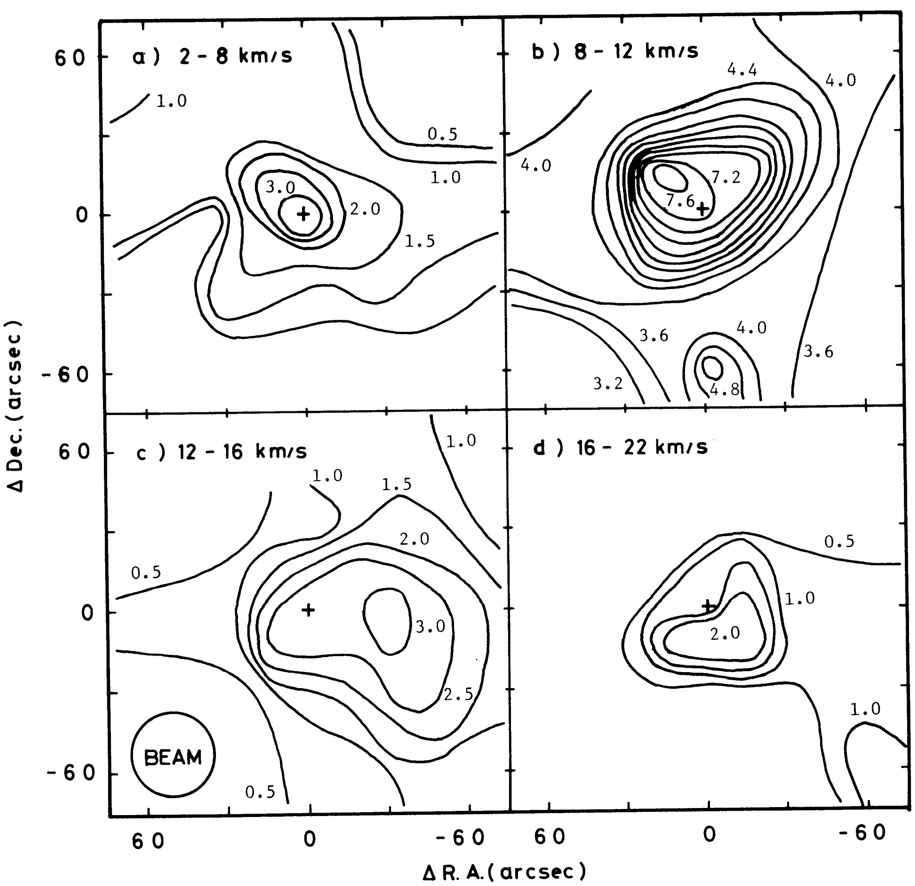

FIG. 2.—Integrated intensity maps for four velocity ranges: (*a*), 2–8 km s^{-1}; (*b*) 8–12 km s^{-1}; (*c*) 12–16 km s^{-1}; and (*d*) 16–22 km s^{-1}. The contour unit is K km s^{-1}. The beam size is shown in panel (*c*). The positions of the infrared sources are shown by a cross in each panel.

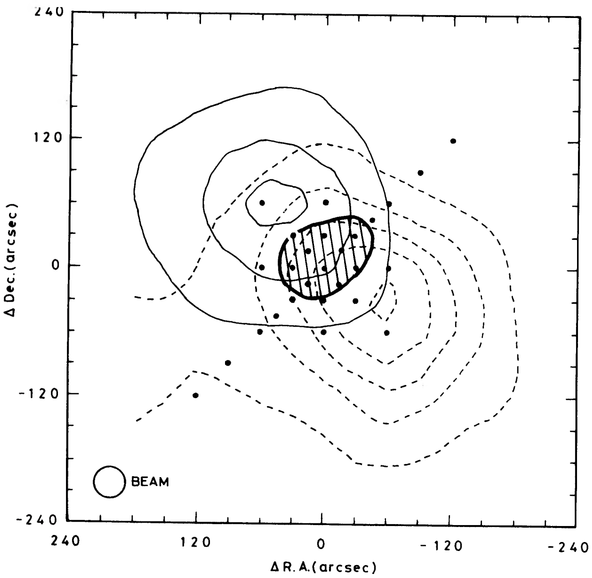

FIG. 3

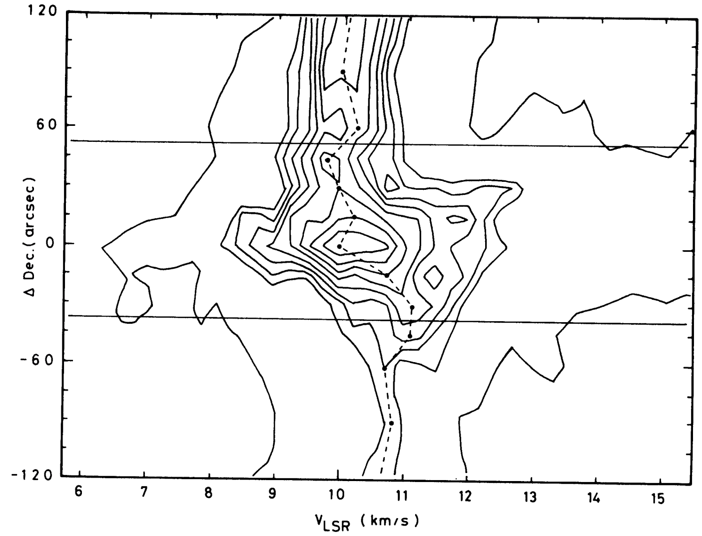

FIG. 4

FIG. 3.—Distributions of the CO bipolar flow and the CS cloud. The contours of the CO integrated intensity are taken from Bally (1982); the solid contours and the broken contours are for the blueshifted CO wing and for the redshifted CO wing, respectively. The dark solid contour with hatching shows the boundary of the compact CS cloud. The observed points are shown by filled circles.

FIG. 4.—Position-velocity diagram along the NW-SE direction, i.e., along the elongation of the compact CS cloud. The edges of the compact CS cloud are shown by two horizontal lines. The lowest contour is 0.2 K, and the second lowest one is 1.0 K. The other contours are every 0.2 K. Filled circles show peak velocity.

estimated to be $\sim 10\ M_\odot$ because the far-infrared luminosity of $\sim 10^3\ L_\odot$ (Sargent *et al.* 1981) implies B3 type if the stars are in ZAMS. The molecular mass plus the stellar mass amounts to a few times 10 $M_\odot$, which is consistent with the dynamical mass if the inclination angle is, for instance, about 60°.

Two aspects of the CS compact disk should be pointed out: (*i*) the mass of the disk ($\sim 10\ M_\odot$) is much smaller than what was suggested for the previously detected extended disk ($\sim 10^3\ M_\odot$), and (*ii*) the internal velocity dispersion of the compact disk is very small, $\Delta v \approx 2$ km s^{-1}. These two points can place constraints on the role of the disk in collimation of the bipolar flow.

One of the most important issues pertaining to the bipolar flows is the collimation mechanism for the bipolar geometry: for this particular object, collimation by the extended CS disk was suggested by Bally (1982). Our present high-resolution data indicate that there is a small and rather quiescent disk in the innermost part, which should be more responsible for collimation of the flow than the extended CS disk because of its proximity to the infrared objects. A consequence of the disk collimation should be a significant expansion of the disk because the disk must have received outgoing momentum comparable to that in the observed CO bipolar flow. We find, however, an upper limit for the expanding momentum set from the present data, (1–6) $\times 10^{39}$ g cm s^{-1}, is significantly smaller than that of the bipolar flow (1.5–4.4) $\times 10^{40}$ g cm s^{-1} (Bally 1982). We infer, therefore, the CS compact disk has not been responsible for focusing of the outflow and that collimation has already occurred at radius smaller than $\sim 10^{17}$ cm. A possibility is that a circumstellar disk of $\lesssim 10^{16}$ cm radius is collimating the flow. We suggest that the strong infrared polarization orthogonal to the bipolar flow (Heckert and Zeilek 1981) may be evidence for such a circumstellar disk.

The authors are grateful to Professor C. Hayashi for enlightening discussion about the disk. Discussion with Dr. S. Ikeuchi improved our understanding of the role of the disk in collimating the bipolar flow. In this connection, the comments by the referee were very stimulating. The staff of the Nobeyama Radio Observatory, a branch of the Tokyo Astronomical Observatory, assisted in making the observations. One of the authors (T. T.) was in part supported financially by the Japan Society for the Promotion of Sciences. This work was in part supported by the Grant-in-Aid for Scientific Research of the Ministry of Education, Science, and Culture (58420004).

REFERENCES

Bally, J. 1982, *Ap. J.*, **261**, 558.
Bally, J., and Lane, A. P. 1982, *Ap. J.*, **257**, 612.
Calamai, G., Felli, M., and Giardinelli, S. 1982, *Astr. Ap.*, **109**, 123.
Heckert, P. A., and Zeilek, M., II. 1981, *A.J.*, **86**, 1076.
Fukui, Y., Ogawa, H., Takano, T., Kawabe, R., and Takaba, H. 1984, presented in *Protostars and Planets II*, Tucson, Arizona.
Lichten, S. M. 1982, *Ap. J.*, **253**, 593.
Persson, S. E., Geballe, T. R., Simon, T., Lonsdale, C. J., and Baas, F. 1981, *Ap. J.* (*Letters*), **251**, L85.
Sargent, A. I., Van Duinen, R. J., Fridlung, C. V. M., Nordh, H. L., and Aalsers, J. W. G. 1981, *Ap. J.*, **249**, 607.
Snell, R. L., Langer, W. D., and Frerking, M. A. 1982, *Ap. J.*, **255**, 149.

M. FUJIMOTO, Y. FUJIMOTO, Y. FUKUI, R. KAWABE, H. OGAWA, K. SUGITANI, H. TAKABA, and T. TAKANO: Department of Physics, Nagoya University, Chikusa-ku, Nagoya, Japan