

ENERGETIC ACTIVITY IN A STAR-FORMING MOLECULAR CLOUD CORE; A DISK CONSTRAINED BIPOLAR OUTFLOW IN NGC 2071

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ABSTRACT

The discovery of an extended, high-velocity molecular outflow associated with the infrared sources in NGC 2071 is reported. High-velocity CO emission from this star-forming molecular cloud core can be traced over a region $4'$ in diameter and detected over a velocity range of 70 km s^{-1} . The flow is bipolar; the blueshifted CO emission is displaced to the northeast, while the redshifted emission is displaced to the southwest. Observations in the 98 GHz transition of CS reveal a ridge of dense gas oriented orthogonal to the high-velocity flow axis. A systematic velocity gradient seen in the CS line core suggests that the ridge is a dense, rotating disk centered on the IR source. The disk may be responsible for collimating a spherically symmetric wind originating near the IR source into the bipolar flow observed in the high-velocity CO line wings. The high-velocity CO line wings are modeled as beam diluted emission from clumps or filaments with ^{12}CO optical depths close to unity and a small filling factor. The clumps may be either objects ejected from the vicinity of the central infrared source or shocked gas at the front where a higher velocity but invisible flow encounters ambient cloud material.

Subject headings: infrared: sources — interstellar: molecules — nebulae: individual —
 nebulae: reflection

I. INTRODUCTION

Since the discovery of broad wings in the molecular emission lines detected from the Orion A cloud core (Zuckerman, Kuiper, and Rodriguez-Kuiper 1976; Kwan and Scoville 1976) broad CO line wings have been found near the luminous infrared sources GL 961 (Blitz and Thaddeus 1981), Cepheus A (Rodriguez, Ho, and Moran 1980), GL 490 (Lada and Harvey 1981), and the Herbig-Haro object, L1551 (Snell, Loren, and Plambeck 1980). In three of these sources (GL 490, Ceph A, and L1551) high-velocity gas is seen from an area nearly 1 pc in diameter. There is mounting evidence for the existence of a previously unrecognized episode of energetic activity associated with star formation in molecular cloud cores. In this paper observations of high-velocity outflow in the star-forming region NGC 2071 are presented.

NGC 2071 is a reflection nebula in the northern part of the Orion B molecular cloud, located at a distance of 500 pc and excited by a B3 star, HDE 290861. An infrared source, buried deep in the cloud behind the reflection nebulosity, was discovered by Strom, Strom, and Vrba (1975). Infrared observations of this object (also known as GL 818) by Harvey *et al.* (1979) indicate a steep spectrum between 2 and $50 \mu\text{m}$ and a total luminosity of $L \sim 750 L_{\odot}$. Both a type I OH maser (Pankonin, Winnberg, and Booth 1977) and an H_2O maser exhibiting rapid variability and several high-velocity components have been reported (Campbell 1978).

Maps of CO at $2.5'$ resolution have been presented by White and Phillips (1981). The CO profile at the infrared source position exhibits strong self-reversal indicating the presence of a cold, absorbing, foreground cloud (Loren *et al.* 1981; White and Phillips 1981). The high-velocity CO emission reported here was detected as part of a systematic survey of luminous infrared sources associated with relatively nearby ($d < 3 \text{ kpc}$) molecular cloud cores.

II. OBSERVATIONS

The mm wavelength data were obtained with the Bell Laboratories 7 m antenna located in Holmdel, New Jersey. A cooled mixer receiver operating with a single sideband noise temperature of $T_{\text{SSB}} = 350 \text{ K}$ was used on conjunction with a 256 channel $1/4 \text{ MHz}$ filter bank. All spectra were obtained in the double position switching mode using two emission-free reference positions, one $60'$ west and another $90'$ east of NGC 2071. The unobstructed off-axis Cassegrain optics of this telescope yield spectra with exceptionally flat baselines when used with the double position switching mode. Spectra were calibrated with a chopper wheel using a two step procedure; chopping between an ambient temperature load and a load at 77 K is used to measure the receiver temperature. Chopping between sky and the cold load gives the sky temperature which is used to calculate the

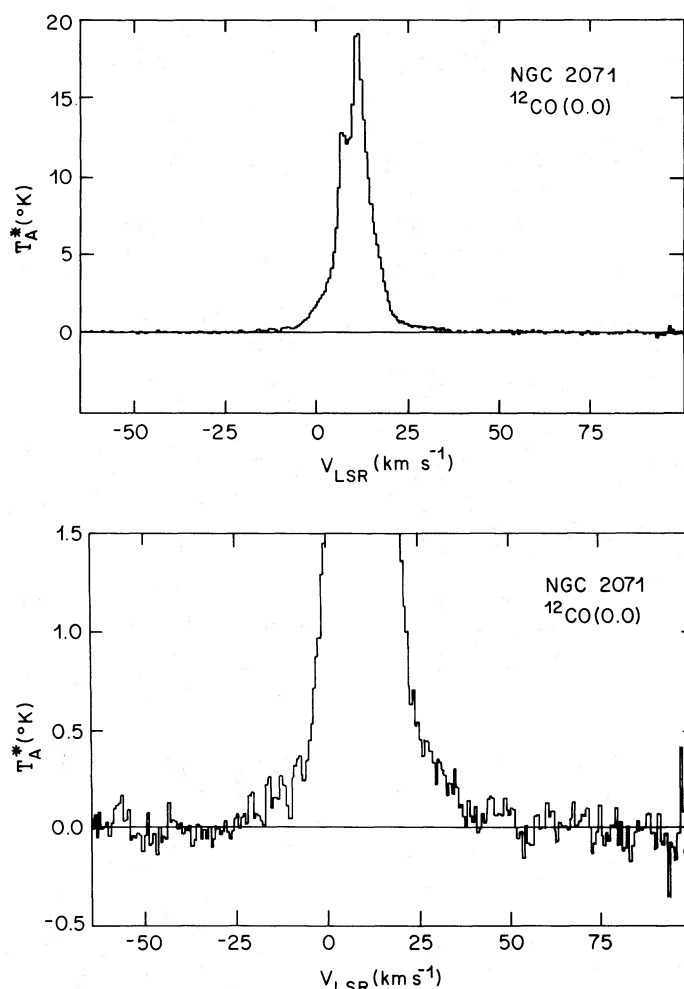


FIG. 1.— ^{12}CO spectra in the direction of the infrared source in NGC 2071 at $\alpha_{1950} = 05^{\text{h}}44^{\text{m}}30^{\text{s}}.0$, $\delta_{1950} = 00^{\circ}20'40''$. (a) The entire spectrum; (b) magnified view showing the high-velocity wings.

system temperature and the value of T_A^* for each channel in the filter bank.

An $8' \times 8'$ grid was sampled at every $1'$ interval in the 115 GHz transition of ^{12}CO (the antenna beamwidth at this frequency is $\theta_{\text{FWHM}} = 90''$). Total integration time per point was adjusted to yield an rms noise of 100 mK or better. (Usually 20 minutes in good sky conditions was sufficient.) Longer integration time was used on the central position in order to measure the full extent of the ^{12}CO emission. Several ^{13}CO and C^{18}O spectra were obtained at source center, and along the major and minor axis of the flow in order to measure column densities in these optically thinner lines and to look for kinematic effects in which most of the gas in the line of sight is participating. The CS:2–1 line at 98 GHz was observed to study the distribution of dense gas in the molecular cloud core. An $8' \times 8'$ region centered on NGC 2071 was mapped on a $2'$ grid. Additional high

sensitivity spectra were obtained along NE–SW and SE–NW strips at $1'$ spacing in order to look for systematic velocity shifts close to the major and minor axes of the bipolar flow seen in CO.

III. CO KINEMATICS

Figure 1 shows the ^{12}CO emission profile at the position of the infrared source at $\alpha_{1950} = 05^{\text{h}}44^{\text{m}}30^{\text{s}}.0$; $\delta_{1950} = 00^{\circ}20'40''$. The core of the line exhibits an absorption dip caused by colder foreground material, thus the highest observed temperature $T_A^* = 19$ K leads to an underestimate of the gas kinetic temperature. Mid-infrared observations (Harvey *et al.* 1979) suggest a dust temperature between 30 K and 40 K in the core NGC 2071. A value of $T_g = 35$ K will be adopted in calculations involving the gas temperature or the CO(1–0)

excitation temperature in the cloud core. Outside the velocity of the self-reversal, the CO line exhibits intermediate velocity wings that extend over a full width of 25 km s^{-1} at a temperature $T_A^* > 1 \text{ K}$. The intermediate velocity wings are detectable in a $4' \times 5'$ region centered on the cloud core; outside this region, the ambient cloud exhibits CO line emission with a full width less than 10 km s^{-1} . The intermediate velocity wings and line core are superposed on a low intensity ($T_A^* < 1 \text{ K}$) pedestal. These high velocity wings cover a full range of $\Delta v = 70 \text{ km s}^{-1}$ at a detection limit of $T_A^* = 50 \text{ mK}$ and are formed in a $2' \times 3'$ region centered on the IR source. Figure 2 shows the spatial distribution of the blueshifted and redshifted intermediate velocity gas. Although the contours appear nearly circular in shape, the source may be extended as observed with the Bell Laboratories antenna. (The projected half-power beam size of the antenna is illustrated in the upper left corner in Fig. 2. About 85% of the power is concentrated within the main beam of this antenna at 115 GHz.) Further evidence for the large extent of the high velocity flow comes from the apparent separation of the centroids of the blueshifted and redshifted emission regions. The angular size of the high velocity emission region must be equal to or larger than the beam size of the Bell Laboratories 7 m antenna.

Both the high and intermediate velocity gas exhibit a displacement of the blue and red line wings in *opposite* directions from the source center. The most prominent blue wings are seen $1'$ northeast of the infrared source, while the most prominent red wings are seen a similar distance to the southwest. The symmetric displacement of the red and blue wings around the source center define a flow major axis that is oriented at $\text{P.A.} = 130^\circ \pm 10$, close to the NE-SW direction. A spatial velocity diagram, constructed from map points lying on a strip crossing NGC 2071 in a NE-SW direction is shown in Figure 3a and clearly illustrates the bipolar morphology of the outflow. The intermediate velocity gas exhibits the same shear as the high-velocity gas; no systematic dependence of velocity on displacement from the infrared source is evident. A spatial velocity diagram constructed from spectra lying on a strip running SE-NW through the infrared source and close to the flow minor axis is shown in Figure 3b. In this direction, the line wings appear symmetric; no displacement is apparent.

The ^{13}CO isotope shows emission in the intermediate velocity wings. Figure 4 shows the ratio of ^{12}CO to ^{13}CO across the line profile at the central (0,0) position. The signal-to-noise ratio in the high-velocity region of the ^{13}CO spectrum ($\Delta v > 18 \text{ km s}^{-1}$) is insufficient to determine the presence or absence of emission. The intermediate velocity ^{13}CO emission shows the NE-SW shear observed in ^{12}CO . The line core, however, which in the ^{13}CO line is single peaked, *does not show any significant velocity shift in the NE-SW direction*. Observations of the C^{18}O line obtained along the flow

major axis also show *no velocity shift*. Since the two rare isotopic species probe the dynamics of the gas in the entire line of sight, the absence of shear in the core of these lines implies that the *bulk of the gas in the line of sight is not partaking in the motion observable in the ^{12}CO and ^{13}CO wings*. The ^{13}CO and C^{18}O line core, however, does show a small velocity gradient in the SE-NW direction (orthogonal to the direction of the velocity gradient seen in the line wings). The SE-NW gradient in the line core is similar to what is seen in the line core of the CS molecule (see below).

A quantitative estimate of the column density of gas in the line core and line wings can be obtained from two sets of line ratios [$T_A^*(^{12}\text{CO})/T_A^*(^{13}\text{CO})$ and $T_A^*(^{12}\text{CO})/T_A^*(\text{C}^{18}\text{O})$]. Using the formalism outlined in Solomon (1978) to compute the column densities of ^{13}CO and C^{18}O , total column densities $N(^{13}\text{CO}) = 1.1 \times 10^{17} \text{ cm}^{-2}$ and $N(\text{C}^{18}\text{O}) = 8.2 \times 10^{15} \text{ cm}^{-2}$ at the (0,0) position are computed. Using a ratio $[\text{H}_2]/[^{13}\text{CO}] = 10^6$ and $[\text{H}_2]/[\text{C}^{18}\text{O}] = 7.14 \times 10^6$ (Frerking, Langer, and Wilson 1982), hydrogen column densities of $N(\text{H}_2) = 1.1 \times 10^{23} \text{ cm}^{-2}$ and $N(\text{H}_2) = 6 \times 10^{22} \text{ cm}^{-2}$ are calculated from ^{13}CO and C^{18}O line profiles, respectively. The disagreement between the two numbers may reflect saturation and fractionation effects in ^{13}CO so the C^{18}O determination is probably more reliable. In this estimate, it is assumed that $T_{\text{ex}} = T_k = T_g = 35 \text{ K}$. If the average gas in the observed column is colder, the calculated column density decreases and the above estimates are upper limits. [For $T = 20 \text{ K}$ $N(\text{H}_2) = 7.5 \times 10^{22} \text{ cm}^{-2}$ and $N(\text{H}_2) = 3.9 \times 10^{22}$ are computed from ^{13}CO and C^{18}O , respectively.]

The mass of high-velocity gas present in this source is difficult to determine unambiguously due to uncertainties about the physical nature of the line emitting region. Possible models for line formation include: (1) low density gas in which the excitation temperature of ^{12}CO is much less than the gas kinetic temperature, (2) gas in which the ^{12}CO optical depth is very small, and (3) a clumpy medium consisting of high-density, high-opacity condensations with a small beam filling factor. Detection of CS emission in the 98 GHz $J = 2-1$ transition from the lower velocity portions of the red and blue lobes of the bipolar flow excludes model (1). Detection of the intermediate velocity CO wings in ^{13}CO suggests that for $\Delta v < 20 \text{ km s}^{-1}$ the ^{12}CO opacity is of order unity or greater. Furthermore, observations of the CO $J = 2-1$ transition at 230 GHz indicate that the intensity ratio of the $J = 2-1$ to $J = 1-0$ transition is close to unity over this velocity range (Loren *et al.* 1981). These data suggest that the high velocity line emission is formed in dense ($n > 10^3 \text{ cm}^{-3}$), opaque ($\tau^{[1/2]\text{CO}} \gtrsim 1$), beam-diluted clumps. In order to estimate the mass, momentum, and energy in the high-velocity flow, it is assumed that the projected area of the emission region is smaller than the beam size with a beam filling factor

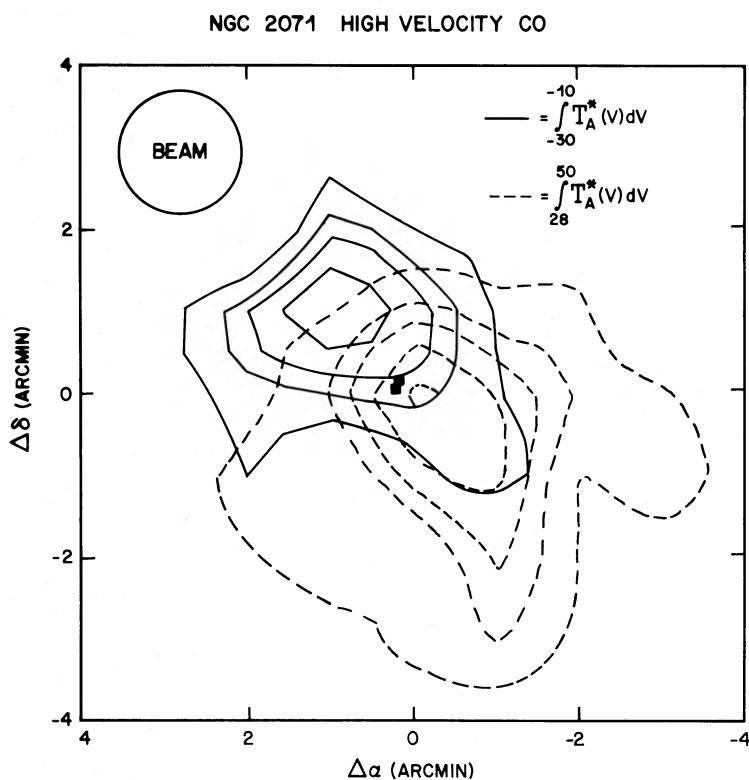
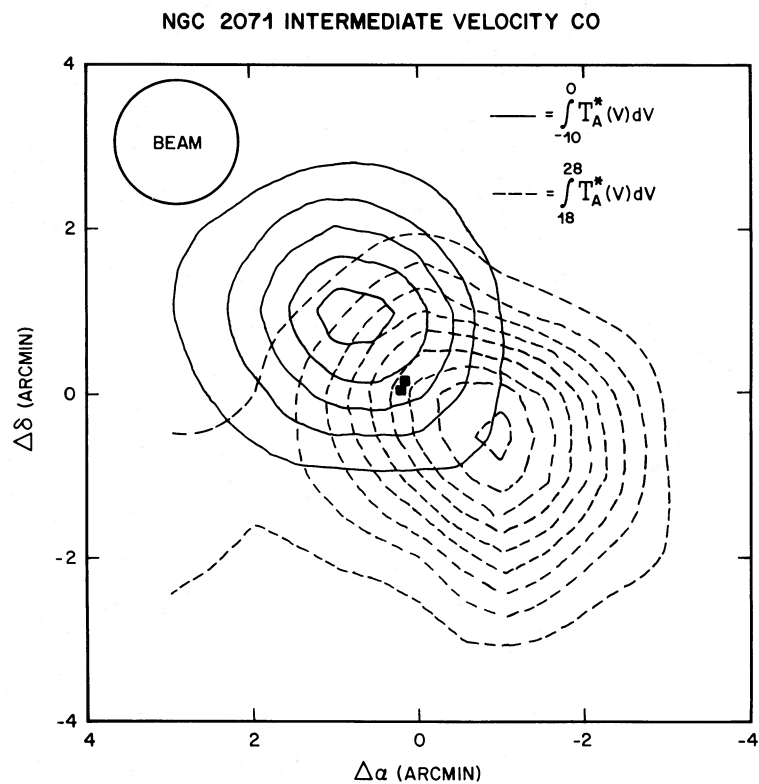


FIG. 2.—(a) Spatial distribution of the intermediate velocity gas in the velocity range indicated in the figures. Contour levels are at 1.5, 3.0, 4.5, 6.0, 7.5, 9.0, 11.5, 12.0, and 13.5 K (km s^{-1}). (b) Spatial distribution of the high-velocity gas with contour intervals at 0.5, 1.0, 1.5, 2.0, and 2.5 K (km s^{-1}). The pair of black boxes near the center of each figure mark the location of the compact H II regions detected by Bally and Predmore (1982).

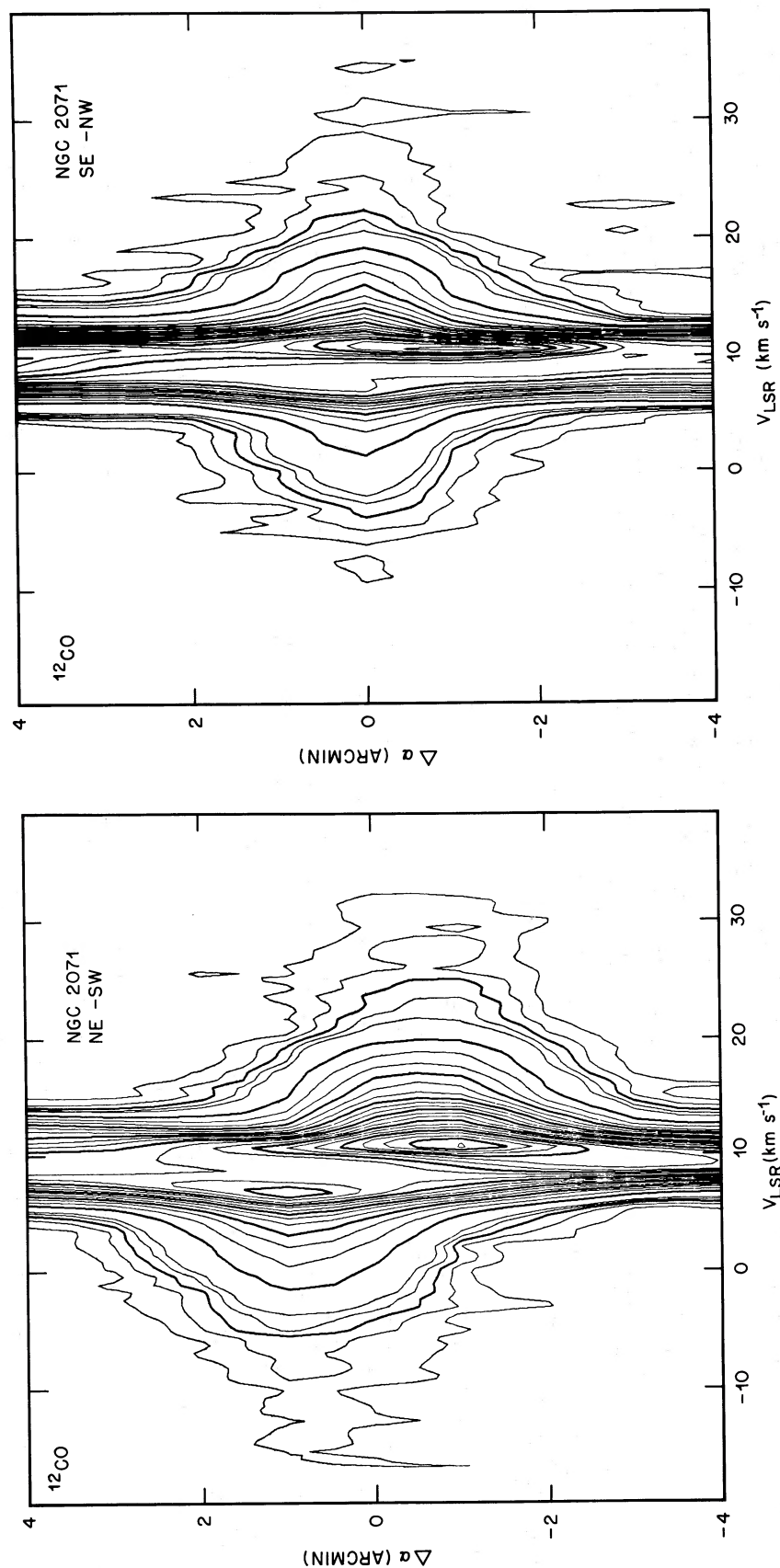


FIG. 3a

FIG. 3b

FIG. 3.—(a) Spatial velocity diagram constructed from ¹²CO spectra running NE-SW through the (0,0) position; (b) spatial velocity diagram constructed from ¹²CO spectra running in the SE-NW direction through the (0,0) position. Contour levels are 0.2, 0.4, 0.6, 0.8, and 1.0 K. All contours after the fifth are at intervals of 1 K. $\Delta\alpha$ scale is in arcminutes of R.A. Actual arclength along each diagram is $\sqrt{2}$ times larger.

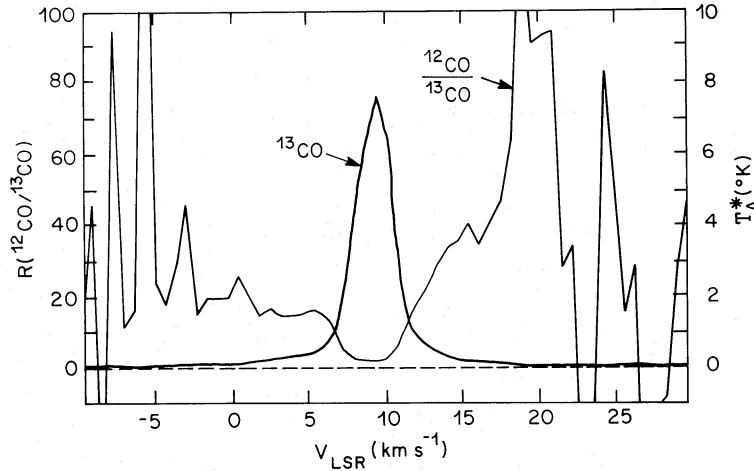


FIG. 4.— ^{13}CO in the core of NGC 2071 and the isotopic ratio ($R = T_A^*(^{12}\text{CO})/T_A^*(^{13}\text{CO})$) across the line profile. At velocities $\Delta v > 18 \text{ km s}^{-1}$, the signal-to-noise ratio is too small to obtain any useful information, and fluctuations dominate the isotopic ratio.

$f(v) \approx T_A^*(v)/T_{ex}$ in each velocity interval. (For $T_{ex} = 10 \text{ K}$, $10^{-3} < f < 0.5$, depending on velocity.)

Over the velocity range in which ^{13}CO is detectable outside the line core, the integrated intensity ratio of the ^{12}CO and ^{13}CO isotopic species is $T_A^*(^{13}\text{CO})/T_A^*(^{12}\text{CO}) \sim 0.04$. Assuming an excitation temperature of 10 K and $^{13}\text{CO}/\text{H}_2 = 10^{-6}$ a molecular hydrogen column density per unit velocity interval $N(\text{H}_2) = 3 \times 10^{20} \text{ cm}^{-2} \text{ km}^{-1} \text{ s}$ is computed. The mass of the high-velocity flow is computed from

$$M = \eta m(\text{H}_2) D^2 \int_{\text{wings}} N(\text{H}_2) f(v) dv$$

where η is a geometrical factor taking into account the bipolar geometry of the flow ($\eta \sim 2$), and D^2 is the area of the sky over which the high velocity CO wings are detectable. The momentum and energy of the flow are computed from the first and second moments of the filling factor weighted column density. Thus

$$P = \eta m(\text{H}_2) D^2 \int_{\text{wings}} N(\text{H}_2) f(v) v dv;$$

$$E = \frac{1}{2} \eta m(\text{H}_2) D^2 \int_{\text{wings}} N(\text{H}_2) f(v) v^2 dv.$$

The velocity width of the line core is taken to be the linewidth observed just outside the outermost boundary of the high-velocity flow region ($\Delta v_{\text{core}} \sim 12 \text{ km s}^{-1}$). With the core excluded, the above integrals yield, for $T_{ex} = 10 \text{ K}$, the values $M = 7.3 M_{\odot}$, $P = 1.5 \times 10^{40} \text{ g cm s}^{-1}$ and $E_k = 2 \times 10^{46} \text{ ergs}$. (For $T_{ex} = 20 \text{ K}$, $M = 12.3 M_{\odot}$, $P = 2.4 \times 10^{40} \text{ g cm s}^{-1}$, $E = 3.2 \times 10^{46} \text{ ergs}$. For $T_{ex} = 40 \text{ K}$, $M = 22 M_{\odot}$, $P = 4.4 \times 10^{40} \text{ g cm s}^{-1}$, $E = 5.8 \times 10^{46} \text{ ergs}$.) The mass density and its

moments are shown in Figure 5. It is instructive to compare these values to the momentum and energy generated by a stellar wind acting over a dynamic time scale $\tau = r/v_{\text{max}} = 2 \times 10^{11} \text{ s}$. For $\dot{M} = 10^{-5} M_{\odot} \text{ yr}^{-1}$ and $V_w = 1000 \text{ km s}^{-1}$, the total momentum generated during a dynamic time scale is $P_w = 1.3 \times 10^{40} \text{ g cm s}^{-1}$ and the total kinetic energy of the wind is $E_{ke} = 6.4 \times 10^{47} \text{ ergs}$.

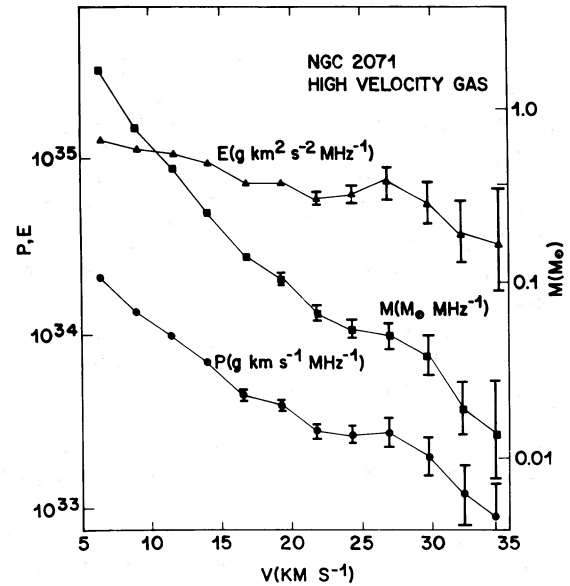


FIG. 5.—The distribution of gas in the high-velocity wings in NGC 2071. The mass, momentum, and energy in a 1 MHz frequency interval (corresponding to $\Delta v = 2.6 \text{ km s}^{-1}$) at each velocity are shown for an assumed excitation temperature $T_{ex} = 10 \text{ K}$. (For $T_{ex} = 40 \text{ K}$ the curves are shifted upward in the plot by roughly a factor of 4.)

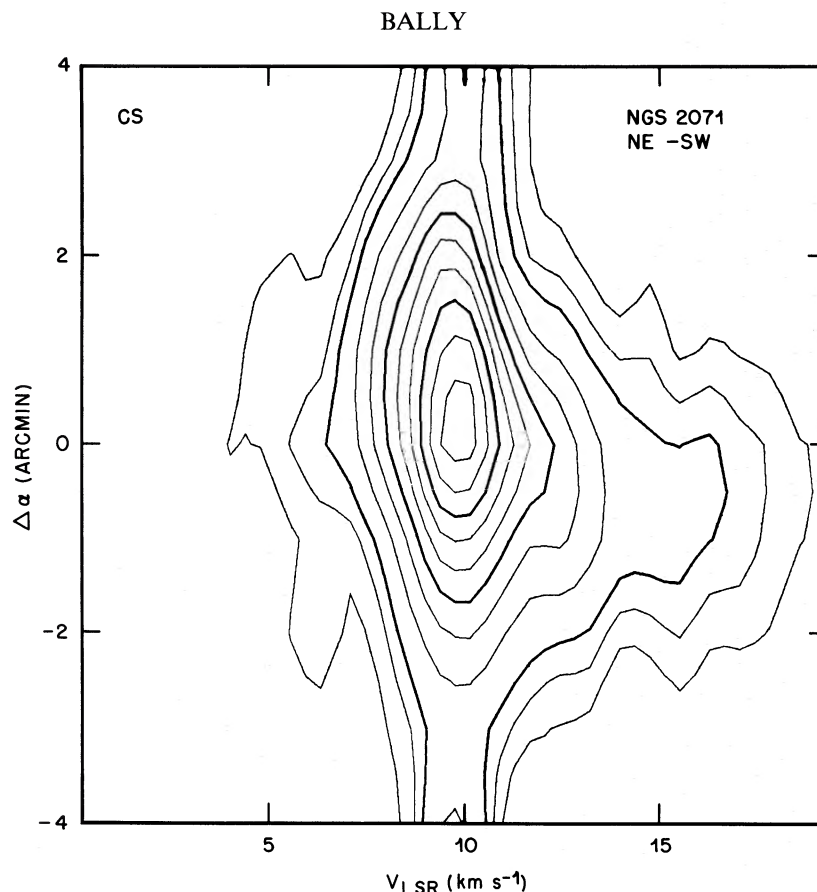


FIG. 6.—Spatial velocity diagram showing the bipolar flow in the CS line in the NE-SW direction. Contours are at 0.1, 0.2, 0.3, 0.5, 0.7, 1.0, 1.5, and 2.0 K (km s^{-1}).

IV. CS OBSERVATIONS

The NGC 2071 cloud core was mapped in the 98 GHz transition of CS. This molecule requires densities above $n \sim 10^4 \text{ cm}^{-3}$ for significant excitation. It is found to be abundant and has no hyperfine structure (Linke and Goldsmith 1980), so it can be used as a probe of the distribution and dynamics of high-density gas. The CS line profile has a 20 km s^{-1} wide pedestal near the cloud center which shows the *same* bipolar symmetry as the CO observations (Fig. 6). In CS, the redshifted emission is several times stronger than the blueshifted portion of the line.

The CS line core shows evidence of a dense ridge of gas orthogonal to the principal axis of the bipolar high velocity flow. Figure 7a shows a map of the peak line temperature, $T_A^*(\text{CS})$, covering the same $8' \times 8'$ region mapped in CO (Fig. 7b). A velocity gradient is seen in the CS line core along the SE-NW diagonal, close to the orientation of the dense ridge and the high velocity flow minor axis (Fig. 8). In the SE corner of the map the line core is centered at $V_{\text{LSR}} = 10.4 \text{ km s}^{-1}$, while in the NW corner it is centered at $V_{\text{LSR}} = 9.5 \text{ km s}^{-1}$. No shift is discernible in the line core in the NE-SW (principal

axis) direction although the *line wings* show shear associated with the bipolar outflow. In the NE corner the CS core is centered at $V_{\text{LSR}} = 10.0 \text{ km s}^{-1}$, while in the SW corner it occurs at $V_{\text{LSR}} = 9.8 \text{ km s}^{-1}$. The SE-NW velocity gradient suggests that the CS ridge is a nearly edge on disk exhibiting rotation along an axis closely aligned with the axis of the bipolar high-velocity outflow. The velocity gradient of the CS line core requires that the mass inside a $4'$ diameter region surrounding the IR source has a value $M > 32 M_{\odot}$. This is a lower limit since optical depth effects in the CS line and emission by foreground or background gas *not* participating in rotation can decrease the observed gradient. It is interesting to note that the projection of the rotation axis on the plane of the sky is parallel (within 20°) to the galactic rotation axis.

The CS observations can be used to estimate the hydrogen density and column density in the CS ridge. For a CS fractional abundance per unit velocity interval $X(\text{CS})/dv/dr = 10^{-10} (\text{km s}^{-1} \text{ pc}^{-1})^{-1}$, typical of giant molecular cloud cores (Linke and Goldsmith 1980), the mean hydrogen density of the NGC 2071 core is in the range $3 \times 10^4 \text{ cm}^{-3} < n(\text{H}_2) < 2 \times 10^5 \text{ cm}^{-3}$ for kinetic temperature $10 \text{ K} < T_K < 40 \text{ K}$. (See Fig. 3 of Linke and

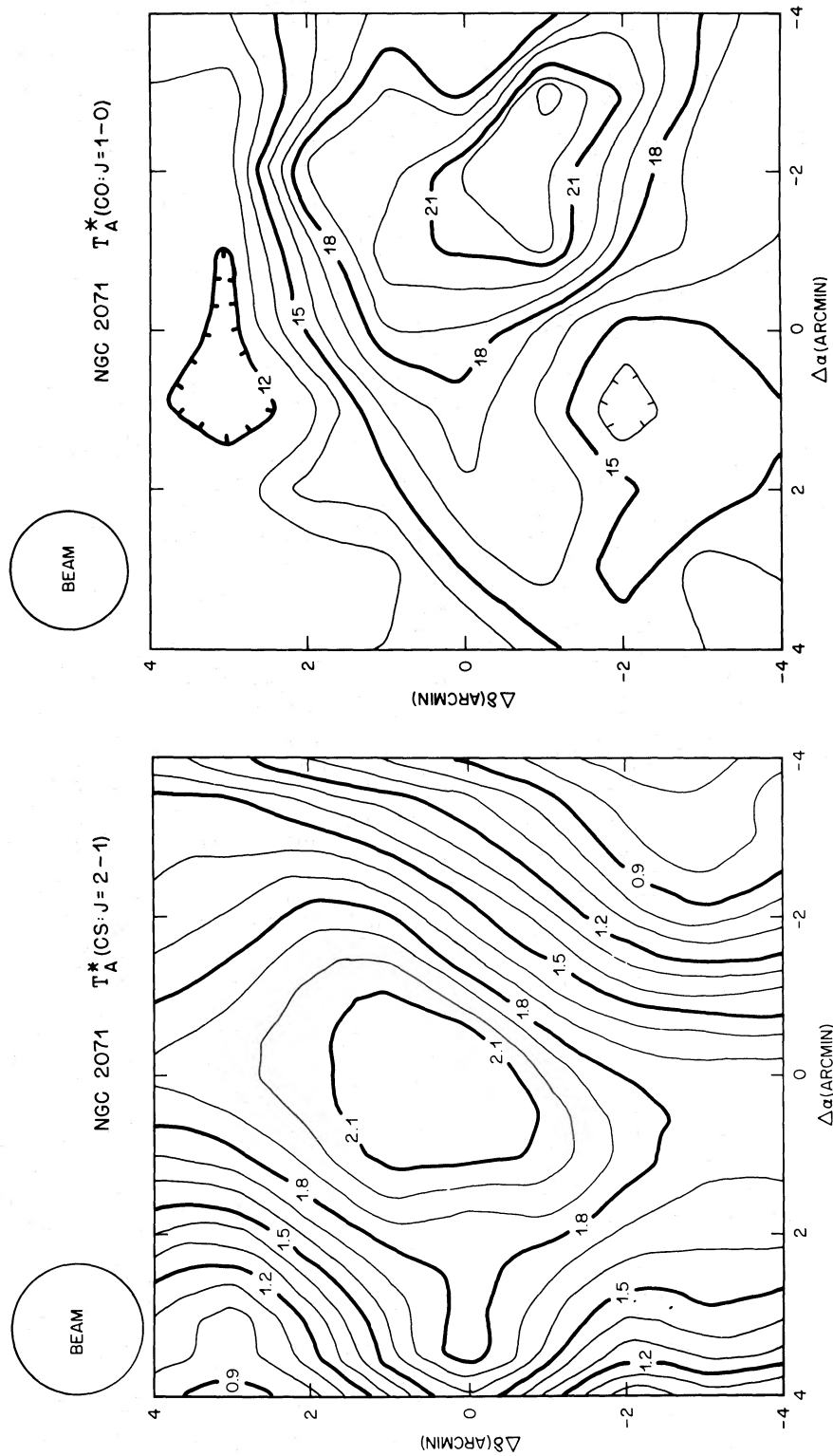


FIG. 7a

FIG. 7b

FIG. 7.—(a) The distribution of CS in NGC 2071 shown by the quantity $T_A^*(\text{CS: } J=2-1)$. Note that the ridge of peak temperature is orthogonal to the axis of symmetry of the bipolar outflow shown in Fig. 3; (b) the distribution of peak CO temperature $T_A^*(\text{CO: } J=1-0)$ is shown for comparison. Note that the peak temperature occurs in the direction of the redshifted line wing. The peak CO temperature occurs on the redshifted side of the self-reversed CO profile (see Fig. 1a).

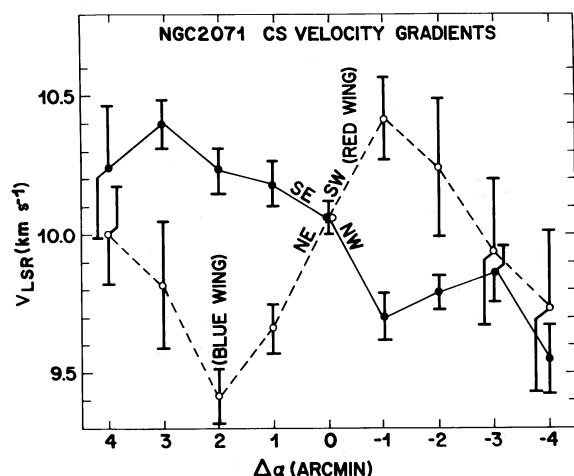


FIG. 8.—Velocity gradients in the CS line centroid along the SE-NW direction (close to the orientation of the CS ridge) and along the NE-SW direction (close to the bipolar symmetry axis). The line velocities were determined by gaussian fit to the CS line core. The line wings are responsible for the velocity gradient in the NE-SW direction.

Goldsmith 1980). The column density of CS is found to be $N(\text{CS}) = 1 \times 10^{14} \text{ cm}^{-2}$ implying a molecular hydrogen column density $N(\text{H}_2) = 2^{+2}_{-1} \times 10^{23} \text{ cm}^{-2}$ [for $X(\text{CS}) = 5 \times 10^{-10}$]. Given the uncertainties, this is consistent with the estimates of column densities based on CO measurements. The mass of the CS ridge can be estimated from this column density. Using $N(\text{H}_2) = 2 \times 10^{23} \text{ cm}^{-2}$, at the infrared source position, the mass within the observed section of the ridge is roughly $10^3 M_\odot$. This is an upper limit on the mass of a circumstellar neutral gas disk that may surround the stars at the center of the high-velocity flow in NGC 2071. Clearly, this mass is sufficient to support the observed SE-NW velocity gradient in the line core of CS, ^{13}CO , and C^{18}O .

V. OTHER RECENT DATA

Several other recent observations have relevance to the interpretation of the high-velocity flow seen in NGC 2071. Bally and Predmore (1982) have discovered a pair of compact H II regions in the center of NGC 2071 with the VLA. The brighter compact H II region, NGC 2071 A, has a flux density of 8 mJy at $\lambda = 6 \text{ cm}$ and is extended with a diameter of about $2''$. A second compact H II region, NGC 2071 B, is found $6''$ to the northwest (at P.A. = 25°) with a flux density of 3 mJy and a diameter of $1.5''$. Persson *et al.* (1981) find two $10 \mu\text{m}$ infrared peaks, IRS 1 and IRS 3, closely coinciding with the compact H II regions. It is interesting to note that IRS 1 and 3 appear to lie within the plane of the rotating core seen in CS and the rarer CO isotopes. Molecular hydrogen emission in the $2.12 \mu\text{m}$ S(1) line has been detected by Bally and Lane (1982) from an

extended region near NGC 2071. Persson *et al.* (1981) report high-frequency resolution observations of the S(1) line that show a width $\Delta v > 100 \text{ km s}^{-1}$.

VI. THE GEOMETRY OF THE HIGH-VELOCITY FLOW

In this section it is shown that the observed line wings indicate outflow (as opposed to rotation, or infall), and the flow geometry is discussed. White and Phillips (1981) noted the velocity shift associated with the intermediate velocity wings in NGC 2071 and argue that it can be explained as rotation around a SE-NW axis. In the light of the high velocities reported here, any gravitationally bound motion is ruled out. The mass required to bind the high-velocity gas (dynamic mass) is one or two orders of magnitude larger than the maximum core mass computed from the observed CO and CS column densities. For a circular velocity of 25 km s^{-1} at a distance of $7 \times 10^{17} \text{ cm}$ from the cloud center (corresponding to a $1/4$ offset from the IR source, the location of the peak wing emission), the mass internal to this radius required for gravitational binding is $3 \times 10^4 M_\odot$. Using a column density $N(\text{H}_2) = 1.1 \times 10^{23} \text{ cm}^{-2}$ derived above, a core mass of $M_{\text{core}} = 280 M_\odot$ is calculated. This represents the *total* amount of mass lying in the entire line of sight in a cylinder of radius $1/4$, and so it is an upper limit to the amount of gas that is in the immediate vicinity of the NGC 2071 core. Even if the mass is increased by a factor of 2 to account for unobservable material, stars, etc., the escape velocity at $r = 7 \times 10^{17} \text{ cm}$ is less than 6 km s^{-1} . The large difference between the dynamic mass and the mass computed from column densities implies that the observed high-velocity wings must be generated in an outflowing gas.

The bipolar geometry of the observed CO outflow can be explained by three distinct configurations.

1) The high-velocity wings form in a swept-up, post-shock layer at the interface between an invisible high-velocity wind and the ambient molecular cloud. The bipolar geometry results from confinement of the wind by a structure such as a disk. The wind escapes in the direction of the disk axis, carving a pair of hemispherical cavities in the molecular cloud. The postshock layer at the cloud-wind interface forms a thin, dense sheet at the outer boundary of the cavity, giving rise to the very small beam filling factors required to explain the observations. The observed momentum in the high-velocity gas requires a wind with a velocity $v \sim 10^3 \text{ km s}^{-1}$ and a mass loss rate $\dot{M} > (\text{few}) \times 10^{-5} M_\odot \text{ yr}^{-1}$ blowing from the vicinity of the compact H II regions.

2) The high-velocity wings form in the wind zone. In this case the wind contains molecules, has a low velocity ($v_w \sim 50 \text{ km s}^{-1}$), and must represent a very large mass-loss rate from the vicinity of the stars at the core of NGC 2071 ($\dot{M} \gtrsim 3 \times 10^{-4} M_\odot \text{ yr}^{-1}$). The postshock layer at the cloud-wind interface has such a low velocity that it blends with the line core and is unobservable.

A neutral molecular wind with $v_w = 50 \text{ km s}^{-1}$ can be driven by ionizing radiation emitted by O and B stars at the cloud center if dense neutral condensations are present close to the star ($r < 10^{16} \text{ cm}$). Ablation and ionization supply plasma to a compact, high-density H II region (Dyson 1969). Isothermal expansion of the plasma establishes an outflow velocity $3c_{\text{II}} < v < 5c_{\text{II}}$ ($c_{\text{II}} \approx 10^6 \text{ cm s}^{-1}$ the isothermal sound speed in an H II region) which transports ionized gas through a quasi static ionization front beyond which it recombines. The gas supplied by ablation from the neutral condensations prevents the expansion of the ionization fronts when a high plasma density is maintained; nevertheless pressure causes expansion of the ionized gas. Molecules may form in the recombining flow beyond the ionization boundary or can be entrained from the surrounding molecular cloud. Confinement of the bipolar flow still requires a disk whose inner portion may be the source of ablating gas preventing expansion of the H II region. This model is discussed in greater detail by Bally and Scoville (1982).

3) The high-velocity wings form in a tilted, expanding disk. The blueshifted emission comes from the near side, while the redshifted emission is formed in the far side of the tilted disk. No specific expansion mechanism is suggested, although gravitational interactions (such as may be caused by a central binary star and its effect on disk particles) are a possibility. Expanding disk models have been used to explain bipolar nebulae surrounding post-main-sequence stars (Morris 1981).

Other models based on anisotropic ejection of material from the cloud core or magnetic confinement of an isotropic flow are possible. The presence of the dense CS-emitting ridge suggests, however, that a disk plays a role in establishing the bipolar structure of the flow. Although it is beyond the scope of this paper to investigate source models in detail, the above three configurations are presented as equally suitable phenomenological descriptions of the available mm-wavelength emission-line data.

VII. CONCLUSIONS

Evidence for the existence of high-velocity, bipolar outflow of molecular gas in the active star-forming molecular cloud core, NGC 2071 has been presented. Broad-line wings can be seen in a region roughly $3' \times 5'$ in extent with the blue wings formed in the NE and the

red wings formed in the SE portion of the source. A cluster of infrared sources and a pair of compact H II regions are located at the center of this region, where the broadest CO emission is seen. Observations of ^{13}CO and C^{18}O show that the ^{12}CO line wings must have an optical depth near unity consistent with a $T_A^*(2-1)/T_A^*(1-0)$ ratio of 1. The high-velocity wings are formed in dense clumps or sheets which at any particular position and velocity range fill only a small fraction of the telescope beam, resulting in low-intensity emission. The low-velocity position of the wings are visible in CS, supporting the hypothesis that the emitting region contains dense condensations.

Several pieces of evidence indicate the existence of a massive molecular disk in the core of NGC 2071. The CS molecule reveals the presence of a ridge of dense gas ($n \sim 10^5 \text{ cm}^{-3}$) oriented orthogonal to the axis of the bipolar outflow. A small velocity gradient is observed, suggesting rotation. The disk may collimate an outflowing wind formed near its center in the direction of the disk poles. A pair of compact H II regions associated with infrared sources at the cloud core may indicate the presence of recently formed B3 or later spectral-type stars whose location is consistent with their formation in the CS emitting disk. These stars may be sources of massive stellar winds or sources of Lyman continuum radiation whose interaction with surrounding dense gas results in the occurrence of energetic mass outflow. The observed high-velocity CO wings may be formed by molecules trapped in the collimated, bipolar wind, or by molecules swept up in a postshock layer at the interface where the wind meets ambient cloud material. An alternative model attributes the high-velocity CO wings to radial expansion of a portion of the disk. The bipolar wind models can explain the extremely broad $\text{H}_2\text{S}(1)$ line emission seen in this source as emission from shocked gas in regions where the wind encounters molecular material. More observational and theoretical work is required to distinguish various possible source geometries and to identify acceleration mechanisms that drive the high-velocity outflow. The strong shock waves generated by the impact of high-velocity flows on the surrounding molecular gas may play a major role in generating supersonic turbulence in molecular clouds. Further study is required to see whether or not these flows may play a vital role in supporting clouds against gravitational collapse, or in triggering further star formation through compression of cloud material.

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