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HIGH-VELOCITY GAS IN THE ORION INFRARED NEBULA

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ABSTRACT

Sensitive observations of carbon monoxide toward the Kleinmann-Low (KL) infrared nebula in Orion have revealed the presence of low-level emission extending over a radial velocity range of at least 150 km s^{-1}. The high-velocity emission appears to be localized to a region $\lesssim 1'$ in diameter centered on KL. The high-velocity gas is probably associated with pre– rather than post–main-sequence object(s). However, the intensity of line radiation at these high velocities is not easily explained with simple models of mass-outflow, gravitational collapse, or rotation.
Subject headings: interstellar: molecules — nebulae: Orion Nebula

I. INTRODUCTION

The evolutionary state of the infrared complex located behind the Orion Nebula has been a subject of considerable uncertainty ever since the discovery of point (Becklin-Neugebauer) and extended (Kleinmann-Low) sources many years ago. On the one hand, there has been controversy over whether the infrared sources are pre– or post–main-sequence stars. On the other hand, if the sources are young it is not certain if they are still accreting matter or whether they have already reversed the accretion and are now dispersing the circumstellar material. There is good reason to believe that radio molecular spectroscopy can help shed some light on these questions. In the present *Letter* we report observations of carbon monoxide emission that appears to originate from the infrared cluster. This emission is distinguished by very broad-line wings (at least ± 75 km s^{-1}). In § II we describe the observations, and in § III we discuss how they relate to the question of the evolutionary state of the infrared complex. A detailed analysis of the shapes of the line profiles in terms of kinematic models of the region, some results of which will be referred to here, will be presented in a later paper (hereinafter called Paper II). A preliminary discussion of these results was presented at the 146th meeting of the American Astronomical Society (Kuiper, Zuckerman, and Rodriguez Kuiper 1975).

II. OBSERVATIONS

Carbon monixide spectra were obtained in 1975 February with the 36 foot (11 m) antenna of the National Radio Astronomy Observatory.[1] The single-sideband system temperature, expressed as an equivalent brightness temperature corrected for atmospheric extinction and beam efficiency (Ulich and Haas 1976), of the cooled mixer receiver was ~900 K. Spectra were obtained with two 256-channel filter banks with 500 and 1000 kHz resolutions. Observations were made by position-switching the telescope every 30 s between the source and a position 30′ away in azimuth. The full half-power beamwidth is ~65″ at the CO frequency (115 GHz). Maps of the CO emission were constructed by obtaining spectra at a total of 26 positions spaced by 30″ in α and δ. The mapping results, which will be reported in detail in Paper II, showed that the broad line wings in Figures 1 and 2 are not the result of baseline curvature since these wings disappear when the telescope is pointed off the infrared cluster.

III. DISCUSSION

a) Pre– or Post–Main Sequence?

It has been suggested on the basis of infrared continuum (Allen and Penston 1974) and radio molecular (Snyder *et al.* 1975) observations that the Kleinmann-Low (KL) infrared cluster or at least one member of it, possibly the Becklin-Neugebauer (BN) source, is a highly obscured post-main-sequence star. Arguments against interpreting the infrared spectra in this way have been presented at various times in the past (e.g., Wynn-Williams and Becklin 1974; Zuckerman 1975). The recently discovered SiO maser in Orion was suggested (Snyder *et al.* 1975; Snyder and Buhl 1974; Kaifu, Buhl, and Snyder 1975) to originate from the

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[1] Operated by Associated Universities Inc. under contract with the National Science Foundation.

circumstellar envelope of an evolved star because of the characteristic shape of the maser profiles and because all other known SiO masers are probably associated with late-type giants. Nonetheless, we believe that it is more likely that the SiO maser in Orion originates from a pre- rather than a post-main-sequence star. Observations of SiO masers during the past 2 years have shown that the Orion source has varied with time appreciably less than the red giant sources (Schwartz and Spencer 1976). Steady infall onto or outflow from a young star might produce maser emission with fairly constant amplitude (see Habing *et al.* 1975).

In addition, the high-velocity CO emission in Figure 1 is unlikely to be related to an evolved star. It has been pointed out that the absence of a substantial H II region associated with KL rules out the possibility that BN or any of the other infrared point sources in KL can be blue main-sequence stars. (Also, such hot stars would probably photodissociate most of the CO in their vicinity.) This requires that the infrared sources be late or intermediate-type giants. But no evidence exists, from studies of OH, H_2O, and SiO masers or optical absorption lines, of outflow velocities from such stars that are as large as the 75 km s^{-1} CO velocities in Figure 1. For example, a recent observation (Giguere and Woolf 1975) of OH maser emission from the F supergiant IRC +10420 suggests that outflow velocities from evolved F stars are comparable with those from M-type giants (<30 km s^{-1}).

Thus, it seems likely that the high-velocity CO gas is associated with young rather than with evolved stars. In that case, we see no reason why the rather modest SiO velocities, as well as velocities of other molecules such as SO, HCN, and H_2S (Zuckerman and Palmer 1975) and SO_2 (Snyder *et al.* 1975), might not be due to the same general gas flows that are responsible for

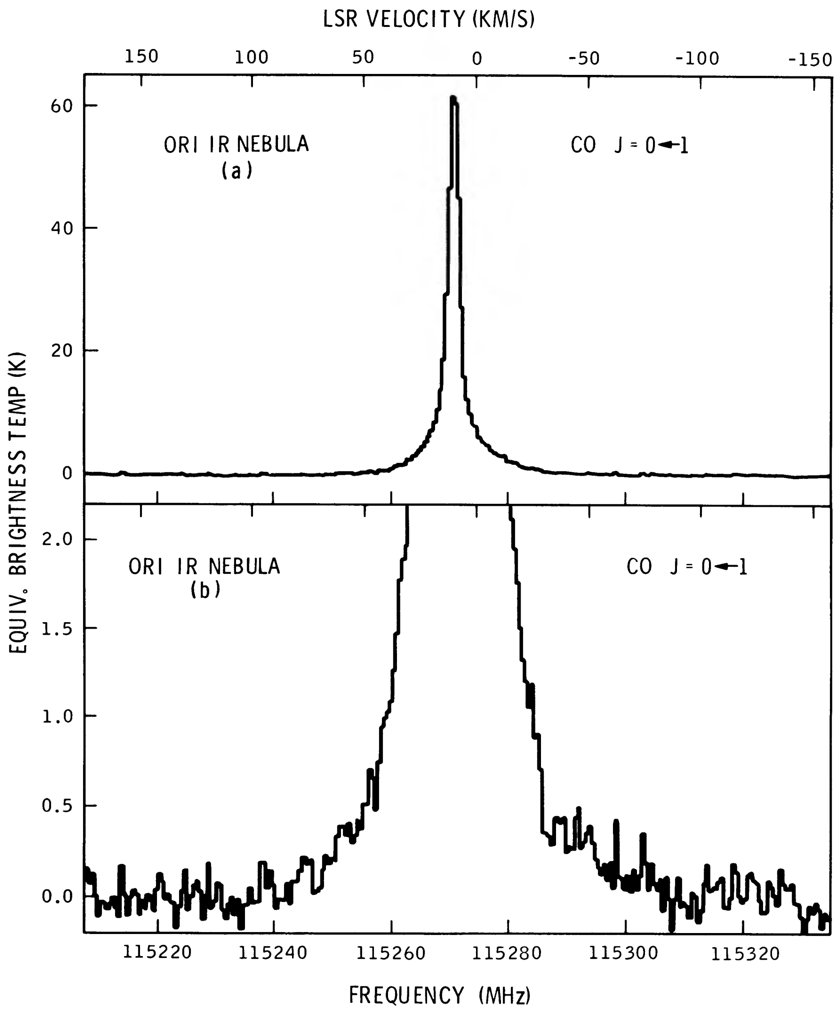

FIG. 1.—Line profiles of the $J = 0 \leftarrow 1$ transition of $^{12}C^{16}O$ toward the Kleinmann-Low infrared nebula. The equivalent brightness temperature is the antenna temperature corrected for atmospheric extinction and antenna beam efficiency. The scale has been adjusted to agree with the calibration of Ulich and Haas (1976). For the velocity scale, a frequency of 115271.2 MHz referred to the local standard of rest was used. For the frequency scale, the LSR velocity was assumed to be +8 km s^{-1}. (Note, however, that the profile peaks at $\sim$9.3 km s^{-1}.) The upper figure (*a*) shows the entire profile, while in the lower figure (*b*), the equivalent brightness temperature scale is expanded to emphasize the line wings. For these data, the 0.5 MHz filters were used.

the CO emission. Precise determinations of the positions of the SiO and high-velocity CO sources should clarify this point. For the time being, it seems most economical to assume that all high-velocity ($|V| \gtrsim 15$ km s^{-1}) molecular emission in Orion is associated with young rather than evolved objects.

b) Infall or Outflow?

In Figure 2 we have fitted Gaussians with velocity widths equal to 6 and 30 km s^{-1} (corresponding to the "spike" and "plateau" features discussed by Zuckerman and Palmer 1975) to the inner part of the CO profile. The extended CO line wings are not Gaussian in shape; this appears to rule out homogeneous turbulence as the line-broadening mechanism. We examine instead models with systematic flows.

We consider first free-fall collapse onto a point mass. Our mapping results establish that the region responsible for the broad CO line wings has a diameter $\lesssim 1'$ ($\equiv 0.134$ pc at the distance of Orion = 460 pc). We assume that the CO is not in maser emission. Then a lower limit to the size of the high-velocity CO source may be obtained by assuming that the $J = 1 \rightarrow 0$ CO line is optically thick and that the excitation temperature, T_s, equals the dust temperature, T_d. At ± 75 km s^{-1} from the line center

$$T_A = 0.1\ K = T_s(\ln 2)p^2/r_B{}^2\ , \tag{1}$$

where T_A, the corrected antenna temperature, is defined in Figure 1. In equation (1), p is the apparent radius of the region that is emitting the CO radiation at the extreme velocities in Figure 2 (see Morris 1975 and Kuiper *et al.* 1976 for a discussion of p in the case of a constant radial flow); $r_B(=0.072$ pc) is the half-power half-beamwidth of the telescope projected to 460 pc; ln 2 is a normalization constant obtained by requiring that the integral over a Gaussian beam pattern is unity.

It is shown in Paper II that for free-fall collapse ($V \propto r^{-1/2}$), the true radial distance from the center of the cloud, r, at which the radial velocity is 75 km s^{-1} is related to p by $r = 2.6p$. The energy radiated by a blackbody of radius r is given by

$$4\pi r^2 \sigma T_d{}^4 = L_s\ . \tag{2}$$

For the line of sight passing directly through the cloud center $T_s = T_d(r)$. For other lines of sight, T_s will be somewhat larger than $T_d(r)$ since CO seen at a line-of-sight velocity of 75 km s^{-1} is somewhat nearer than r to the center of the source. In Paper II we estimate that if $T_d \propto r^{-1/2}$ then, averaged across the CO source, $T_s = 1.1\ T_d(r)$. The brightest infrared point sources in Orion have bolometric luminosities $< 1.6 \times 10^4\ L_\odot$ (Rieke, Low, and Kleinmann 1973; Wynn-Williams and Becklin 1974). Setting $L_s = 1.6 \times 10^4\ L_\odot$ and solving equations (1) and (2) along with the relations between r and p, and T_s and T_d, yields $T_d = 125$ K and $r = 1250$ AU ($\sim 2\farcs7$).

Superficially, a 5″ diameter region having a temperature of 125 K might be associated, for example, with the core of KL. A serious problem with this association arises, however, if the ± 75 km s^{-1} CO velocities are due to free-fall collapse. Then, the mass of the 5″ region is

$$M = V^2 r/2G \approx 4000\ M_\odot\ . \tag{3}$$

That such a small, massive cloud should actually exist in Orion seems unlikely for several reasons. Unsupported, the cloud will collapse in a free-fall time scale of less than 100 years. However, in the 10 years that have elapsed since its discovery, the intensity of KL has not varied appreciably. This, combined with the improbability of observing such a short-lived phase in stellar evolution, suggests that the cloud is no longer collapsing, but is accreting material onto a "surface" at 1200 AU or less.

A quasi-hydrostatic cloud containing 4000 $M_\odot$ that fragments with moderate efficiency into stars according to a standard Salpeter mass function (Salpeter 1955) would be much more luminous than the core of KL. Because there is no optical evidence for the existence of such massive, tightly bound star clusters, the cluster would have to dissolve—but this would produce a much larger number of high-velocity stars than is observed. To avoid such problems, one might envision the formation of only a few stars followed by a catastrophic disruption of the rest of the cloud, as described for example by Appenzeller and Tscharnuter (1974). However, comparisons of the masses of compact H II regions and their associated stars suggest that, at least within regions ~ 1000 AU in size, star formation is a rather efficient process (e.g., Zuckerman and Palmer 1974; Habing 1975).

Even ignoring the infrared evidence, the gas kinetic temperature could not exceed ~ 5000 K without CO becoming dissociated. If we take the extreme case of 5000 K as the CO excitation temperature, the minimum size of the region is $\gtrsim 200$ AU. Hence, unless the CO is masing, the mass in a hydrostatic core must still be larger than $\sim 700\ M_\odot$ so that the previous arguments against this model still apply.

Therefore, we conclude that it is unlikely that collapse onto a massive object is responsible for the extended CO line wings. Rotation appears no more likely than collapse since the required mass is of comparable magnitude.

Outflow models are not without their own problems. The main difficulty arises in matching the detailed shape of the CO profile in Figures 1 and 2. Outflow velocities $\gtrsim 100$ km s^{-1} have been deduced for many young stellar objects including, for example, Ae, Be, and T Tauri stars and Herbig-Haro objects (Strom, Strom, and Grasdalen 1975) as well as O and B stars. The difficulty arises in that "standard" acceleration mechanisms such as stellar winds (Parker 1964; Mufson and Liszt 1975) and radiation pressure (Kwok 1975) accelerate material rapidly near the star and then the material "coasts" at essentially constant velocity until it bumps into something and is decelerated. In the spherically symmetric case such acceleration mechanisms produce flat-topped or parabolic line shapes as observed, for example, in IRC +10216 (Morris 1975; Kuiper

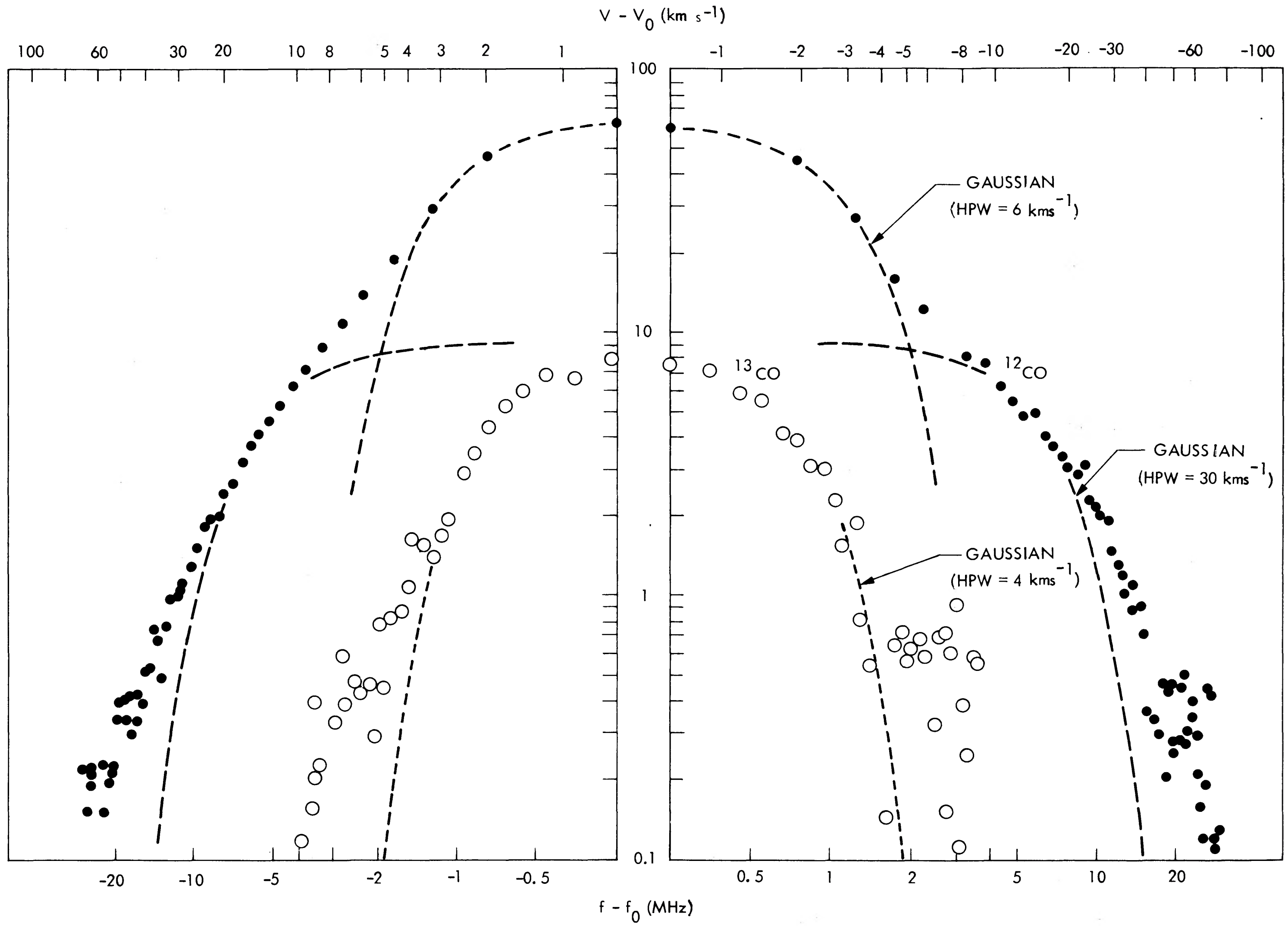

FIG. 2.—Profiles of ^{12}CO and ^{13}CO in the direction of the Kleinmann-Low nebula, plotted with logarithmic coordinates. The vertical axis represents equivalent brightness temperature (defined in Fig. 1). The velocity ($V - V_0$) and frequency ($f - f_0$) scales are relative to the center of the ^{12}CO profile (see Fig. 1).

et al. 1976) rather than a profile with extended wings as in Figure 1. The shapes of line profiles in spherically symmetric cases will be considered in detail in Paper II.

Before considering possible acceleration mechanisms, we estimate the mass of gas associated with the high-velocity wings:

$$M/M_{\odot} \approx 1.4 \times 10^{-52} \bar{n}_{CO} k p^2 L \,, \tag{4}$$

where $\bar{n}_{CO}$ (cm^{-3}) is the average CO density throughout the region giving rise to radiation between line-of-sight velocities V_z and $V_z + \Delta V_z$, p(cm) is the apparent radius of this region, L(cm) is its average depth along the line of sight, and k is a numerical constant depending on the details of the geometry (see Paper II; when the inflow or outflow velocity is proportional to r, the emitting volume is a planar slab, and $k = 1$). The above expression assumes $n_{CO}/n_{H_2} \approx 5 \times 10^{-5}$ and a 14 percent relative number abundance for helium. The column density of CO within a velocity interval ΔV_z is given by

$$\bar{n}_{CO} L \approx 4.2 \times 10^{13} \tau \bar{T}_s^2 \Delta V_z \,, \tag{5}$$

where $\bar{T}_s$ is the average excitation temperature throughout the volume giving emission between V_z and $V_z + \Delta V_z$ (expressed in km s^{-1} relative to the center of the line). Now, analogous to equation (1),

$$\tau \bar{T}_s \gtrsim T_A r_B^2/(p^2 \ln 2) \,, \tag{6}$$

where the lower limit applies in the optically thin case. Substituting (5) and (6) into (4) with $k \sim 1$, and adopting an appropriate analytical expression for the line wings in Figure 2 for $|V_z| \gtrsim 20$ km s^{-1}, we find

$$M/M_{\odot} \gtrsim 5.2 \bar{T}_s [V_{\min}^{-1.6} - 10^{-3}] \tag{7}$$

for the line wings between $V_{\min} \leq |V_z| \leq 75$ km s^{-1}. For example, with $\bar{T}_s = 70$ K, $M = 0.8\ M_{\odot}$ for $V_{\min} = 35$ km s^{-1}, and 2.6 $M_{\odot}$ for 20 km s^{-1}. Since the high-velocity region is not resolved by the telescope beam, for a mean outflow velocity of 75 km s^{-1} the outflow time is $\sim$1000 yr unless the acceleration mechanism is very unusual. Direct mass loss of $\sim 10^{-3}\ M_{\odot}$ yr^{-1} is difficult to account for.

One conceivable outflow model for the CO emission requires that the region surrounding the young stellar objects in the infrared cluster be very nonuniform and contain numerous dense blobs of gas separated by lower density holes and tunnels. Such a situation might occur, for example, at the time of the breakup of the dust cocoons (Kahn 1974). Then, high-velocity stellar winds might transfer their momentum to the surrounding dense molecular gas blobs. Such nonuniformities in molecular clouds have been suggested to explain Herbig-Haro (HH) objects (Strom, Grasdalen, and Strom 1974) and molecular line profiles (Zuckerman and Evans 1974). Gull *et al.* (1973) have reported a Herbig-Haro object in the Orion Nebula. Subsequently, another HH object was found and more may exist (Gull 1975, 1976). Both objects are elongated in directions pointing toward KL. In spectral lines characteristic of low excitation and high density (Hα; S II $\lambda\lambda$6717, 6731; N II $\lambda\lambda$6548, 6584; O I $\lambda\lambda$6300, 6363) a low-intensity wing is seen extending 200–300 km s^{-1} toward the blue. The KL region may contain a cluster of A and B stars each of which is losing mass at a rate of $10^{-6}\ M_{\odot}$ yr^{-1} at a velocity of 300 km s^{-1} (Strom, Strom, and Grasdalen 1975). If the momentum in these winds is transferred to globs of molecular gas which are accelerated to velocities of $\sim$75 km s^{-1}, then $\sim$100 such stars are required to satisfy the time and mass constraints discussed above.

A second conceivable acceleration mechanism for CO involves the rocket effect (Oort and Spitzer 1955). One of the infrared point sources, say BN, may already have evolved sufficiently that it is surrounded by a small H II region (e.g., Grasdalen 1976). Then it is possible that, if the Oort-Spitzer mechanism really accelerates rather than heats or dissipates clouds (e.g., Spitzer 1968) sufficient mass might be accelerated to produce the observed CO profiles. In the simple rocket model, $M_{\rm final} = M_{\rm initial} \exp\ (-V_{\rm final}/V_{\rm exhaust})$. If $V_{\rm exhaust}$ equals the sound velocity in an H II region, $M_{\rm initial}/M_{\rm final} \sim 50$. The high-velocity CO gas could then be a remnant of a much more massive neutral cloud that has since been ionized. However, the fairly low luminosity of the infrared point sources and the absence of a radio continuum source in KL would seem to preclude the existence of such ionized gas.

IV. SUMMARY

High-velocity carbon monoxide emission toward the Kleinmann-Low infrared nebula promises to be a useful tool to probe its evolutionary state. Arguments have been presented which suggest that the high-velocity gas is associated with pre– rather than post–main-sequence objects. Models involving free-fall collapse or rotation require a very large mass ($\gtrsim 1000\ M_{\odot}$) and a very low efficiency of star formation in a fairly small region ($\sim$1000 AU). For these reasons, outflow models seem more attractive, but these do not readily explain the CO line shape, and the inferred mass-loss rates are difficult to account for. Future observations with greater sensitivity might reveal CO gas at even larger velocities than those shown in Figure 1. An interferometric determination of the size and location of the source of high-velocity emission would be extremely valuable. Sensitive observations of ^{13}CO may establish whether the ^{12}CO line wings are optically thick or thin, thus restricting the range of possible models. Observations of other molecules may reveal additional characteristics of the high velocity source.

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