THE ASTROPHYSICAL JOURNAL, **251**:103–107, 1981 December 1

HIGH VELOCITY MOLECULAR GAS NEAR HERBIG-HARO OBJECTS HH 7–11

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Received 1981 March 9; accepted 1981 June 15

ABSTRACT

Observations of the $J = 2$–1 and $J = 1$–0 transitions of ^{12}CO and ^{13}CO reveal the presence of high velocity molecular gas associated with a low luminosity infrared source in the vicinity of the Herbig-Haro objects HH 7–11. The blueshifted and redshifted wings show peak intensities spatially separated by 1.′5 (0.2 pc), suggesting an energetic bipolar outflow of gas from a young low mass star. The mass loss rate implied by these observations is $8 \times 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$.

Subject headings: interstellar: molecules — stars: mass loss — stars: pre-main-sequence

I. INTRODUCTION

The recent discoveries of high velocity wings in CO profiles associated with young stellar objects indicate the existence of a hitherto unexplored phase of stellar evolution. The broad-winged sources detected to date include Ori A (Kwan and Scoville 1976; Zuckerman, Kuiper, and Kuiper 1976; Scoville 1981) L1551 (Snell, Loren, and Plambeck 1980), Cep A (Rodriguez, Ho, and Moran 1980), AFGL 490 (Lada and Harvey 1981), and AFGL 961 (Blitz 1980). The large CO velocity dispersions ($\Delta V > 30$ km s^{-1}), often distributed anisotropically about an embedded infrared source, have been attributed to energetic mass outflows from these embedded objects. We report the detection of an additional candidate for this new class of objects, centered on a low luminosity infrared source near the Herbig-Haro objects HH 7–11.

The Herbig-Haro objects HH 7–11 lie south of the reflection nebula NGC 1333 illuminated by the B9 V star BD+30°549. The presence of T Tauri stars, Hα emission stars, Herbig-Haro objects, and near infrared sources all indicate that this is an active star forming region (Herbig 1974; Strom, Grasdalen, and Strom 1974). The distance to NGC 1333 has been determined by Strom, Grasdalen, and Strom (1974) to be 500 pc based on spectroscopic and photometric observations of BD+30°549. Most of the young stellar objects are embedded in a large molecular cloud which has been studied by Lada *et al.* (1974) and Loren (1976). The NGC 1333 molecular cloud is part of a larger cloud complex associated with the Perseus OB2 association (Sargent 1979). The mass of the entire cloud complex has been estimated by Sargent (1979) to be roughly $10^4\ M_\odot$ of which roughly $10^3\ M_\odot$ is associated with the NGC 1333 region (Lada *et al.* 1974). Loren (1976) has suggested that star formation has been initiated by the collision of two molecular clouds.

Near-infrared mapping (Strom, Vrba, and Strom 1976) has revealed the presence of several sources near HH 7–11. Source number 13, in the list of Strom, Vrba, and Strom (1976), is the closest to HH 7–11 and was suspected by Schwartz (1981) to be the exciting star for the Herbig-Haro objects. This infrared source is coincident with a far-infrared source detected by Harvey (1981). Hereafter this infrared source will be labeled HH 7–11 IR; the coordinates of this source are given by Cohen and Schwartz (1980) to be R.A. (1950.0) = $03^h25^m58^s.2$, decl. (1950.0) = +31°05′46″. Three H_2O maser sources have been identified near HH 7–11 (Haschick *et al.* 1980) and have been found to be unusually small and rapidly varying in both intensity and velocity. One of the H_2O maser sources, H_2O(A), is coincident with HH 7–11 IR. The Herbig-Haro objects and IR source are also coincident with one of the peaks seen in the maps of NH_3 emission (Ho and Barrett 1980) and CS emission (Lada *et al.* 1974). The mass of the fragment containing HH 7–11 has been estimated by Ho and Barrett (1980) to be $230\ M_\odot$.

We have searched for high velocity gas associated with young stellar objects in the NGC 1333 region; high velocity gas was found only in the vicinity of HH 7–11. We present in this Letter high spatial resolution $J = 1$–0 and $J = 2$–1 ^{12}CO and ^{13}CO data obtained around HH 7–11. These spectra show spatially extended blueshifted wings indicating the presence of high velocity gas which is probably associated with HH 7–11 IR. The physical properties of the high velocity material in this region are examined and the implications for mass ejection from young stellar objects and its effect on the molecular cloud dynamics are discussed.

II. OBSERVATIONS

The J = 1–0 ^{12}CO and ^{13}CO observations were obtained using the Five College Radio Astronomy Observatory (FCRAO) 14 m telescope located in New Salem, Massachusetts. A low noise cryogenic receiver utilizing quasi optics for calibration and sideband rejection (Predmore *et al.* 1980) was used with a 256 channel filter bank spectrometer with 250 kHz spectral resolution. The receiver had a single sideband noise temperature of roughly 450 K. Calibration of the data was established using an ambient temperature chopper wheel. The beam size and beam efficiency were measured by mapping Jupiter and were found to be 50″ and 0.36, respectively. The efficiency on an extended source, determined by measuring the Moon, was found to be 0.62.

The $J = 2\text{–}1$ ^{12}CO and ^{13}CO data were obtained at the Millimeter Wave Observatory (MWO)[1] in Fort Davis, Texas using the 4.9 m telescope and a receiver developed at FCRAO. The receiver is a cryogenic version of that described by Erickson (1981). Typically two 128 channel filter bank spectrometers, one with 1 MHz spectral resolution and the other with 250 kHz spectral resolution, were used. The receiver had a single sideband system temperature of 1000 K. The data were calibrated using an ambient temperature chopper wheel and assuming equal gains and equal atmospheric opacity in both sidebands (both are good assumptions since the sidebands were separated by only 2.8 GHz). Measurements of the Moon and Jupiter determined the beam size to be roughly 1′.3, the beam efficiency to be 0.45, and the efficiency on extended sources to be 0.84. The observations were made with both telescopes operating in a position switching mode.

III. RESULTS

Figure 1 shows the ^{12}CO and ^{13}CO $J = 1\text{–}0$ spectra obtained toward HH 7–11 IR. The ^{12}CO profile consists of a narrow component at $V_{LSR} = 7$ km s^{-1} arising from the large scale molecular cloud (Lada *et al.* 1974) and a broad wing component extending from V_{LSR} of -20 to $+20$ km s^{-1}. A similar velocity structure is also observed in the $J = 2\text{–}1$ ^{12}CO spectra. The broad feature is asymmetrical with a greater velocity extent to the blue side of the narrow component. There is no evidence for high velocity gas in either the $J = 1\text{–}0$ or the $J = 2\text{–}1$ ^{13}CO spectra. We have measured a limit to the integrated intensity of high velocity gas in both ^{13}CO spectra. Comparing these limits to the integrated intensity of the high velocity gas observed in ^{12}CO, we find that the observed isotopic ratio for the $J = 2\text{–}1$ line is $^{12}\text{CO}/^{13}\text{CO} > 56$, and for the $J = 1\text{–}0$ line is $^{12}\text{CO}/^{13}\text{CO} > 84$. These results are consistent with the terrestrial isotopic ratio of 89, indicating that the ^{12}CO wings are probably optically thin.

The distribution of ^{12}CO $J = 1\text{–}0$ emission was mapped at 36 positions around HH 7–11 IR. The broad wings were found to have a limited spatial extent and to be distributed asymmetrically around HH 7–11 IR. The narrow component was detected over the entire region with little change in strength. The integrated intensity of the blue (integrated over the velocity range of -20 to $+3$ km s^{-1}) and red (integrated over the velocity range $+11$ to $+25$ km s^{-1}) high velocity wings are plotted separately

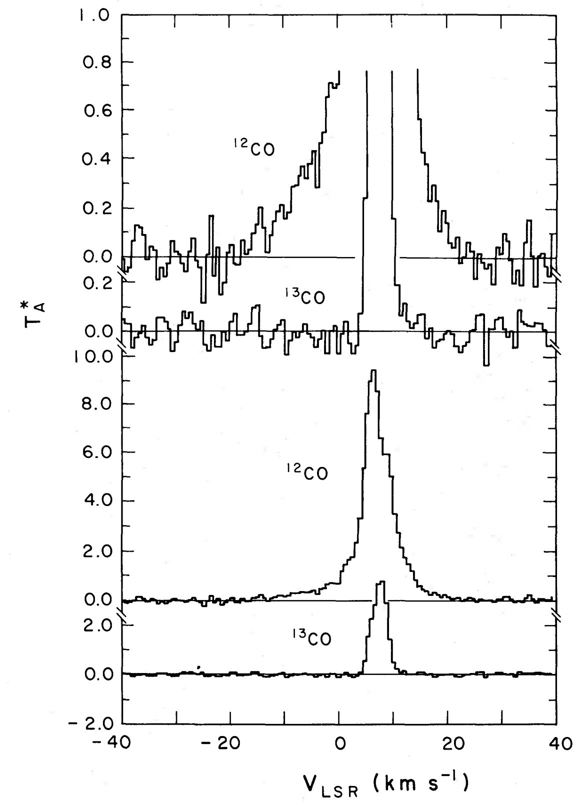

FIG. 1.—The $J = 1\text{–}0$ ^{12}CO and ^{13}CO spectra obtained toward HH 7–11 IR. The upper half of the figure is a 10 × enlargement of the lower half to illustrate the high velocity wings in the ^{12}CO spectra and their absence in the ^{13}CO spectra.

in Figure 2. The velocity extent of the narrow component of 4 km s^{-1} was determined from observations well removed from HH 7–11 IR. A displacement in the maximum integrated intensity of the blue and red wings is seen, with an angular separation of 1′.5 which corresponds to 0.2 pc. HH 7–11 IR is located between the regions where the blue and red wings have their maximum intensity, suggesting a physical association between the high velocity gas and HH 7–11 IR. The coincidence of the maximum intensity of the blueward wing with HH 7–11, which all exhibit negative radial velocities ranging from -139 to -30 km s^{-1} (Strom, Grasdalen, and Strom 1974), suggests a common origin for the Herbig-Haro objects and the high velocity CO gas.

Also indicated on the map in Figure 2 are the positions of other objects in the vicinity of HH 7–11 IR. These include three H_2O masers (Hashick *et al.* 1980), several infrared sources (Strom, Vrba, and Strom 1976), and the Herbig-Haro objects 6, 7–11, and 12 (Herbig 1974). ^{12}CO spectra were obtained at the positions of HH 6 and at the position of two infrared sources near HH 12 (Cohen and Schwartz 1980). Spectra were also obtained toward the T Tauri stars LHα 270 and LHα 271 and toward the infrared sources near HH 4 and 17 and HH 18 (Strom, Vrba, and Strom 1976) which lie outside the boundary shown in Figure 2. No CO high velocity wings were found except in the immediate vicinity of HH 7–11 IR.

[1] The Millimeter Wave Observatory is operated by the Electrical Engineering Research Laboratory of The University of Texas at Austin with support from the National Science Foundation and McDonald Observatory.

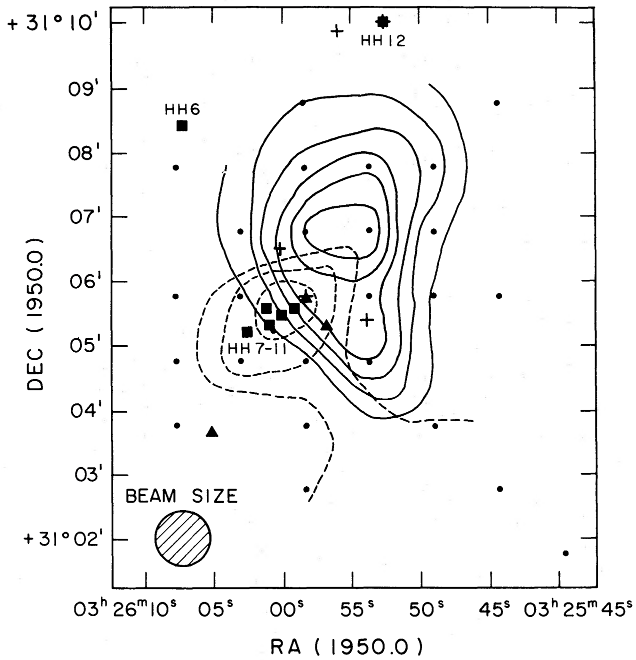

FIG. 2.—Map of the integrated intensity of the redshifted (*solid contour lines*) and blueshifted (*dashed contour lines*) high velocity $J = 1\text{–}0$ ^{12}CO gas near HH 7–11. The intensity was integrated over the velocity range of -20 to $+3$ km s^{-1} for the blueshifted wings and over the velocity range of $+11$ to $+25$ km s^{-1} for the redshifted wings. The lowest contour shown is for 4 K km s^{-1}, and the contours are in steps of 2 K km s^{-1}. Positions of Herbig-Haro objects (*squares*), H_2O masers (*triangles*), and infrared sources (*crosses*) are marked. The three infrared sources near HH 7–11 are from left to right numbers 14, 13, and 16 from the catalog of Strom, Vrba, and Strom 1976; source number 13 is HH 7–11 IR. Small dots indicate the positions where spectra were obtained; spectra were also obtained at the positions of HH 6, HH 12, and the infrared source near HH 12.

Figure 3 presents ^{12}CO $J = 2\text{–}1$ spectra taken at six positions along the northwest to southeast axis that coincides with the maximum high velocity $J = 1\text{–}0$ emission centered on HH 7–11 IR. The spatial separation of the blueshifted and redshifted high velocity gas is clearly seen in these spectra. The self-reversal, which occurs over a large portion of the NGC 1333 complex (Loren 1976), is more prominant in the $J = 2\text{–}1$ spectra than the $J = 1\text{–}0$ spectra because of the higher velocity resolution in the $J = 2\text{–}1$ spectra and because of the enhanced redshifted wing which provides a stronger continuum for the foreground material to absorb.

In order to compare the intensity of the $J = 2\text{–}1$ line to the $J = 1\text{–}0$ line in the high velocity gas, it is necessary to correct the data for the forward beam coupling efficiency. Since the size of the emission region of the redshifted or blueshifted high velocity gas is larger than the beam size at either of the CO transitions but small compared to the size of the Moon, we have assumed that the forward beam coupling efficiency is the same as the measured beam efficiency. After correction, the ratio of intensities of $J = 2\text{–}1/J = 1\text{–}0$ in the high velocity gas toward HH 7–11 IR is 1.5 in the blueshifted gas but varies between 2 in the near red wing to 3.5 in the highest velocity redshifted gas. Enhanced $J = 2\text{–}1$ emission is also observed in the redshifted gas at positions 1N–1W and 2N–2W and in the blueshifted gas at a position of 1S–1E; in these positions the intensity ratio is roughly 1.5 to 2.5. The effects of errors in pointing and differences in the beam sizes at the $J = 1\text{–}0$ and $J = 2\text{–}1$ CO frequencies both will cause our estimates of the $J = 2\text{–}1/J = 1\text{–}0$ ratio to be too small. In fact since the region of blueshifted high velocity emission is smaller than the region of redshifted high velocity emission, the smaller ratio observed in the blueshifted gas may be in part due to the differences in the beamwidths. Strong enhancements in the redshifted high velocity gas have also been observed in the ratio of $J = 3\text{–}2/J = 1\text{–}0$ ^{12}CO in this vicinity by White, Phillips, and Watt (1981). These observed intensity enhancements confirm that the ^{12}CO high velocity emission is not optically thick.

The observed intensity ratio of $J = 2\text{–}1/J = 1\text{–}0$ can be used to determine the excitation temperature of the high velocity gas (Goldsmith, Plambeck, and Chiao 1976). The $J = 2\text{–}1$ excitation temperature implied by the ratio of 1.5 in the blueshifted gas toward HH 7–11 IR is roughly 10 K, but excitation temperatures greater than 25 K and possibly greater than 50 K are implied by the large ratios

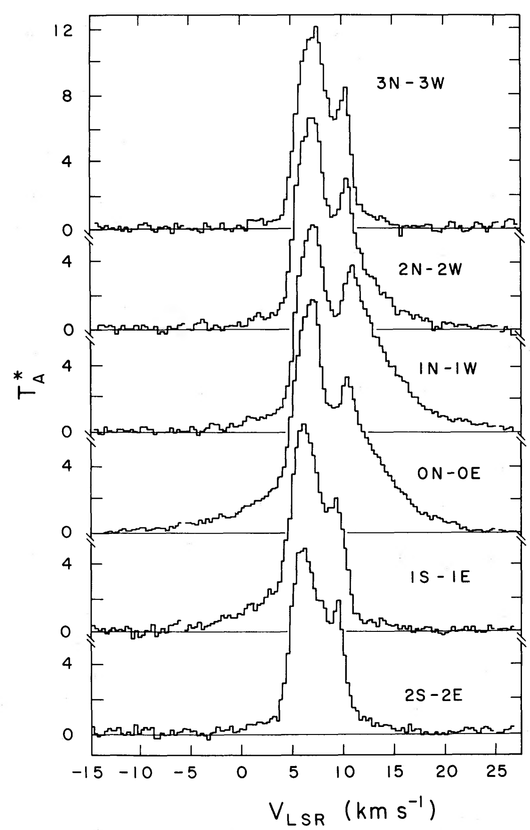

FIG. 3.—The $J = 2\text{–}1$ ^{12}CO spectra obtained at six positions along a southeast to northwest axis through HH 7–11 IR. The offsets by each spectrum are relative to HH 7–11 IR. These spectra clearly show the asymmetry of the redshifted and blueshifted high velocity wings about HH 7–11 IR.

in the redshifted high velocity gas. The ratios of 1.5 to 2.5 measured in the blueshifted gas to the southeast and in the redshifted gas to the northwest imply excitation temperatures of 10 to 25 K. The excitation temperatures derived place a lower limit on the kinetic temperature of the high velocity gas. The observations indicate that the kinetic temperature of the redshifted high velocity gas toward HH 7–11 IR is substantially higher than the kinetic temperature of the ambient cloud derived from the intensity of the narrow CO component. There is no evidence that the blueshifted high velocity gas is hotter than the ambient cloud, but the excitation temperature places only a limit on the kinetic temperature since the blueshifted high velocity gas may not be thermalized and because the ratio may be underestimated as discussed above.

The column density of CO high velocity gas can be determined, assuming that the high velocity ^{12}CO emission is optically thin. The column density is given by: $N_{CO} = 3.5 \times 10^{14} \int T_R\, dv/f_u$ cm^{-2}, where f_u is the fraction of the population in the upper state, T_R (in Kelvins) is the radiation temperature ($T_R = T_A$*/forward beam coupling efficiency), and v is in km s^{-1}. Based on large-velocity-gradient radiative transfer calculations, the fraction f_u in the $J = 1$ state varies slowly with density and kinetic temperature; a value of 0.25 for f_u will be assumed here. As described above, we will also assume that the forward beam coupling efficiency is equal to the beam efficiency. If we assume an H_2/CO abundance ratio of 2×10^4, the total column density of gas is given by: $N = 2.8 \times 10^{19} \int T_R\, dv$ cm^{-2}. The column density of high velocity gas toward HH 7–11 IR is 6×10^{20} cm^{-2}. Summing over the region in which the redshifted and blueshifted wings were detected results in an estimate of 4.2 $M_\odot$ for the total mass of high velocity gas. This total is comprised of 1.3 $M_\odot$ of blueshifted gas and 2.9 $M_\odot$ of redshifted gas. The errors in our mass estimates are all systematic errors stemming from our assumptions on the optical depth of the ^{12}CO wings and on the abundance of CO; both of which are difficult to evaluate. But if the abundance of CO is uniform and both the redshifted and blueshifted wings are optically thin, the difference in the mass of redshifted and blueshifted gas is significant.

The observations of this region indicate the following: (1) high velocity gas is present and probably associated with HH 7–11 IR; (2) the redshifted and blueshifted high velocity gas is spatially separated and occurs on opposite sides of HH 7–11 IR; (3) the ^{12}CO high velocity gas is optically thin; (4) the kinetic temperature of at least the redshifted high velocity gas is much higher than the kinetic temperature of the ambient molecular gas; and (5) the total mass of high velocity gas is 4.2 $M_\odot$.

IV. DISCUSSION

The similarities between the properties of the HH 7–11 region to those found for L1551 (Snell, Loren, and Plambeck 1980), Cep A (Rodriquez, Ho, and Moran 1980), and AFGL 490 (Lada and Harvey 1981) suggest similar origins. The asymmetrical, high velocity gas associated with these embedded infrared sources could result from rotation, collapse, or expansion. As demonstrated by Lada and Harvey (1981), rotation and collapse can be eliminated because of the large central mass necessary to account for the observed velocities. In the case of HH 7–11 IR, a central mass of 10^4 $M_\odot$ in a radius of 0.5 pc is required. Such a large central mass is inconsistent with the mass estimates from NH_3 observations (Ho and Barrett 1980) and with the observed total luminosity of this region. A preliminary estimate of 70 $L_\odot$ for HH 7–11 IR has been provided by Harvey (1981). Thus, as with AFGL 490, Cep A, and L1551, expansion seems the most probable explanation for the high velocity material in the HH 7–11 region. Expansion is also consistent with the symmetric high velocity wings observed toward Ori A (Kwan and Scoville 1976).

The motions of the Herbig-Haro objects associated with the high velocity wings in L1551 and HH 7–11 IR provide further evidence that mass outflow from a young embedded star is occurring. In L1551 the close spatial and velocity coincidence of HH 28 and 29 with the blueshifted high velocity gas suggests a common origin, namely outflow from IRS5 driven by stellar winds. The HH objects 7–11 are also spatially associated with the blueshifted CO wings and show negative radial velocities ranging from -30 to -150 km s^{-1}, which are consistent with a model in which both the HH objects and the high velocity gas are produced by stellar winds from HH 7–11 IR. Such a model provides an explanation for the negative radial velocities measured for most HH objects (Strom, Grasdalen, and Strom 1974), since only those HH objects associated with material ejected toward us will eventually emerge from the cloud to become optically visible objects. Further evidence for expansion from HH 7–11 IR is the spatial coincidence of a H_2O maser, H_2O(A), found by Hashick *et al.* (1980) to have negative radial velocities varying from -10 to -30 km s^{-1}. Rodriguez *et al.* (1980) have suggested that H_2O masers may be high velocity condensations ejected from young stellar objects.

Invoking a stellar wind can account for the presence of high velocity gas, but the anisotropy of the blueshifted and redshifted material is more difficult to explain. Snell, Loren, and Plambeck (1980) suggest that the stellar wind may be confined into a bipolar flow by the presence of an equatorial disk. In both HH 7–11 IR and L1551 IRS5, the bipolar flows are aligned with the direction of the polarization vectors in these regions (Turnshek, Turnshek, and Craine 1980; Vrba, Strom, and Strom 1976), suggesting a possible magnetic confinement of the stellar wind or magnetic alignment of the disk.

Perhaps even more remarkable is the range in luminosities of the infrared sources presumably driving the high velocity expansion in L1551, HH 7–11 IR, Cep A, and AFGL 490. Low luminosities of 25–70 $L_\odot$, characteristic of the more luminous T Tauri stars, are found for L1551 IRS5 (Fridlund *et al.* 1980) and HH 7–11 IR (Harvey 1981). Luminosities two to three orders of magnitude larger characterize Cep A and AFGL 490 (Koppenaal *et al.* 1979; Harvey *et al.* 1979). Apparently stars with vastly different luminosities share similar mass loss events in the course of their pre–main-sequence evolution.

A mass loss rate from HH 7–11 IR can be estimated by requiring conservation of momentum between the stellar wind and the swept up molecular gas. The mass loss rate, $\dot{M}$, is given by the following relation; $\dot{M}v_w = m_g v_g \tau_g^{-1}$, where v_w is the stellar wind velocity, and m_g, v_g, and τ_g are the mass, velocity, and dynamical time scale for the high velocity molecular gas. Using this expression for the mass loss rate explicitly assumes that the mass loss is a continuous process over the dynamical time scale and not a single event. Since there are currently no observations which can discern between these two possibilities, we will assume the flows are continuous but remember that the mass loss rate that is derived is an average over the dynamical time scale. The dynamical time scale is estimated from the extent and velocity of the high velocity gas; for HH 7–11 IR $\tau_g = 2 \times 10^4$ yr. The quantity $m_g v_g$ is determined at all positions by summing over small velocity intervals in the blue and red wings. The resultant $\dot{M}v_w = 1.7 \times 10^{-3} M_\odot$ yr^{-1} km s^{-1}. For a wind velocity of 200 km s^{-1}, the mass loss rate from HH 7–11 IR is 8×10^{-6} $M_\odot$ yr^{-1}. This mass loss rate is similar to that derived for L1551 but less than that estimated for the more luminous sources AFGL 490 and Cep A.

The total kinetic energy of the high velocity gas in the HH 7–11 IR region is 7×10^{45} ergs. The kinetic energy of the 4 $M_\odot$ of high velocity gas is comparable to the kinetic energy of the 230 $M_\odot$ of ambient gas; the total kinetic energy is greater than the gravitational potential energy of the cloud (Ho and Barrett 1980). Norman and Silk (1980) have suggested that high velocity winds from low mass stars can explain the longevity, energetics, and dynamical structure of dark molecular clouds. In the case of L1551 and HH 7–11 IR, low luminosity sources (probable low mass stars) are capable of providing a continuous input of mechanical energy sufficient to prevent the collapse of the cloud. High velocity wings on CO lines have also been observed in two T Tauri stars (Edwards and Snell 1981), indicative of stellar wind interaction with molecular cloud material. The luminosities and mass loss rates for these T Tauri stars are similar to those of L1551 IRS5 and HH 7–11 IR. The interaction of a high velocity stellar wind and ambient cloud material can also explain the high kinetic temperatures measured for the high velocity gas in both L1551 IRS5 and HH 7–11 IR.

The observations of high velocity gas around HH 7–11 IR can best be explained by the interaction of a stellar wind with ambient cloud material. Some unknown mechanism, possibly related to the local magnetic field, channels the wind into a bipolar flow. Both H_2O masers and Herbig-Haro objects are seen around HH 7–11 IR and are probably associated with the blueshifted high velocity flow. The absence of high velocity wings associated with the other young objects in the NGC 1333 region, including T Tauri stars and other infrared sources associated with HH objects, remains puzzling. The observations of HH 7–11 IR and other sources cited here do, however, indicate that some young stars of both high and low mass go through an evolutionary stage in which they have a high rate of mass loss. The kinetic energy transferred to clouds via stellar winds may have important consequences on the energetics of molecular clouds.

We wish to thank R. Schwartz and M. Cohen for helpful suggestions and P. Harvey for communicating results in advance of publication. Also we wish to thank N. Erickson for assisting in the $J = 2$–1 CO observations. The Five College Radio Astronomy Observatory is operated with support from the National Science Foundation under grant AST 80-26702 and with permission of the Metropolitan District Commission, Commonwealth of Massachusetts. This is contribution number 485 of the Five College Astronomy Department.

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