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EVIDENCE FOR PROTOSTELLAR WIND-CLOUD INTERACTIONS

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ABSTRACT

Recent molecular line observations of HH flows (HH objects and optical jets) have revealed abundant evidence of interactions between protostellar winds and the surrounding molecular clouds. HCO^+ observations taken with the BIMA Array have traced out the distribution of both stationary and high-velocity gas near the protostellar objects HH 7-11, L1551, and HH 34.

HH 7-11

Rudolph and Welch (1988) observed HCO^+ emission from HH 7-11 with the BIMA Array. An overlay of the HCO^+ emission with the $H\alpha$ emission from the HH objects shows a striking correlation of the peaks of line intensity with the positions of the optical HH objects. The velocities of the clumps of HCO^+ emission are comparable to the systemic velocity of the cloud implying that the clumps are almost stationary. The narrow linewidths of the HCO^+ emission ($\Delta v \lesssim 0.5\,\mathrm{km\,s^{-1}}$) suggest that the clumps of emission are quiescent. This coincidence of quiescent *almost stationary* ambient gas with the fast-moving shock-excited HH's suggests that HH 7-11 are the shocked surfaces of stationary dense ambient cloudlets buffeted by a high velocity stellar wind.

L1551 IRS 5

HCO^+ observations with $10'' \times 8''$ resolution were made of a $2'$ region around L1551 IRS 5 with the BIMA Array(Rudolph 1992). Figure Ia shows a spectrum of L1551 IRS 5 in $2.1\,\mathrm{km\,s^{-1}}$ wide channels. The channels from −40 to $0\,\mathrm{km\,s^{-1}}$ are clearly elevated above zero. To improve the signal-to-noise in this spectrum, maps with $10\,\mathrm{km\,s^{-1}}$ width were made, and a spectrum of IRS 5 was again taken. This spectrum is shown in Figure Ib. The blueshifted HCO^+ wing now clearly stands out above the noise level, confirming that this emission is real. The wing emission is roughly constant with velocity, and has an average brightness of 0.6 K. A map of the channels from −40 to $0\,\mathrm{km\,s^{-1}}$ reveals that this emission is unresolved and comes only from a region around IRS 5 smaller in extent than the $10''$ beam (2×10^{16} cm). There is no evidence in the spectrum for redshifted gas.

The broad linewidth of this blueshifted gas makes it extremely unlikely that

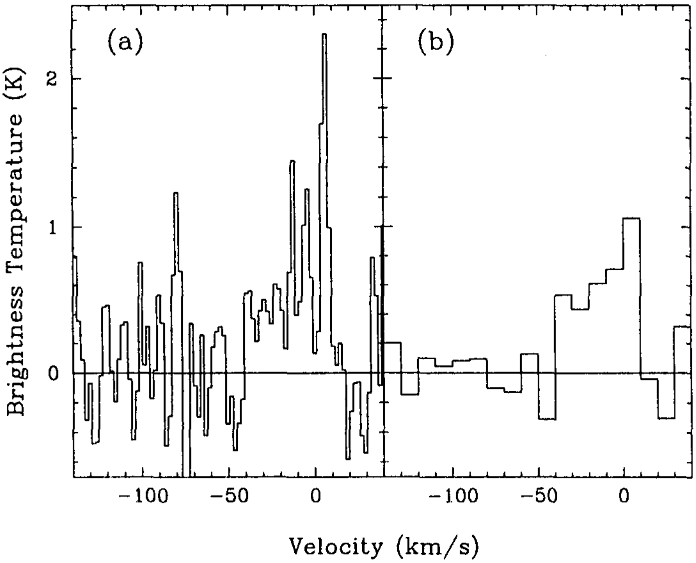

FIGURE I (a) Low-velocity resolution ($2.1\,\mathrm{km\,s^{-1}}$) HCO^+ spectrum of L1551 IRS 5. Note the broad blue wing. (b) The same spectrum taken with $10\,\mathrm{km\,s^{-1}}$ channels. The blue wing is now quite prominent.

this emission is coming from a single, fast-moving clump. Rather, the observed rectangular line shape is consistent with emission from a constant velocity, fast wind. For a maximum observed velocity of $50\,\mathrm{km\,s^{-1}}$, the implied maximum velocity of the gas is $90\,\mathrm{km\,s^{-1}}$.

H I emission has been observed in L1551 at velocities up to $+150\,\mathrm{km\,s^{-1}}$ (Gionvanardi *et al.*1992), corresponding to a deprojected velocity of the neutral wind of $260\,\mathrm{km\,s^{-1}}$. Thus, the HCO^+ gas has a velocity lower than that of the neutral wind, but higher than that of the large-scale CO flow (Snell & Schloerb 1985). This intermediate velocity suggests that the HCO^+ is material entrained by the wind, not material in the neutral wind.

Assuming optically thin emission and LTE at a temperature, T, the momentum carried by the HCO^+ gas is $P = (1.0/\eta)(T/50)\ M_\odot\,\mathrm{km\,s^{-1}}$, where the abundance of HCO^+ relative to H_2 is $2 \times 10^{-9}\eta$. The momentum in the blue wing of the CO flow is $8.7\,M_\odot\,\mathrm{km\,s^{-1}}$ (Moriarty-Schieven and Snell 1988), and since the crossing time for the gas detected in HCO^+ is 700 times shorter than for the CO outflow, the high-velocity gas carries $(80/\eta)$ times more momentum flux than the CO flow. Thus, this gas has more than enough momentum flux to drive the observed CO flow. This result is the first time that gas with sufficient momentum flux to drive an observed CO flow has been discovered with good enough angular resolution to clearly identify the gas as coming from the protostar.

The large implied overabundance of momentum flux in the HCO^+ gas, when compared to the CO outflow, can be explained in at least two ways. First, the HCO^+ abundance might be enhanced compared to values found in quiescent

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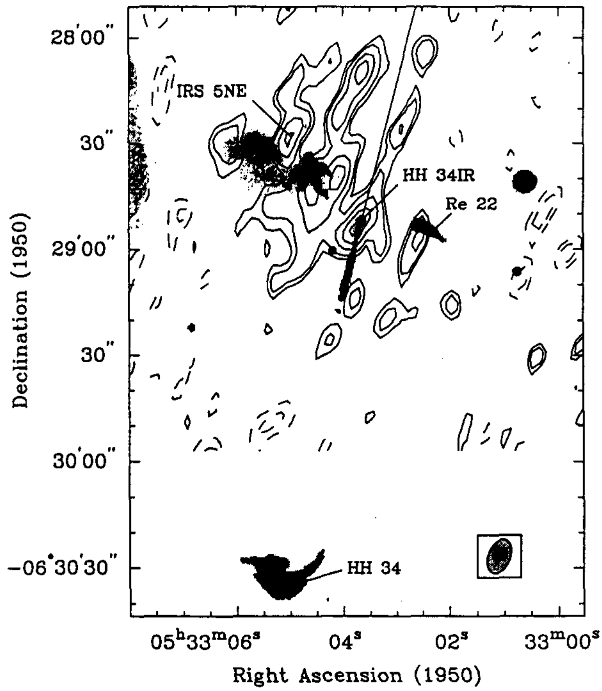

FIGURE II HCO$^+$ emission around HH 34 IR, overlaid on a sum of [S II] and Hα emission from the region. The contours levels are $(-3, -2, 1.5, 2, 3, 4, 5, 6) \times 1.4\,\mathrm{K}\,(1\sigma)$. $1\,\mathrm{K} = 0.4\,\mathrm{Jy/beam}$. Dashed contours are negative. The synthesized beam ($10'' \times 6''$ @ $-20°$) is displayed in the lower right-hand corner of the plot.

clouds ($\eta \gg 1$–4). Second, the wind might be sporadic, so that the CO gas contains momentum collected over many violent outbursts rather than from a single continuous flow.

HH 34

Rudolph and Welch (1992) observed HCO$^+$ emission from the optical jet associated with HH 34. Figure II shows the sum of the two channel maps with emission, covering a velocity range of $8.20-9.25\,\mathrm{km\,s^{-1}}$, overlaid with a composite [S II] + Hα image of the region (Reipurth & Heathcote 1992). Most striking is the extended emission to the north and northwest of HH 34 IR, in roughly a U shape. The line extending from the optical jet to the northwest shows the direction of an expected counterjet emanating from this same central source. Clearly, this line falls between the two arms of the U seen in HCO$^+$ emission, which suggests that these ridges represent the limb-brightened walls of a cavity through which the unseen counterjet flows.

In order to determine if the two northwest ridges are indeed limb-brightened walls of a cavity, the brightness contrast between the ridges and the intervening

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space was measured, and was found to be 2–3. Simple geometry then shows that the inner radius of the shell is at least 90% of the outer radius, *i.e.*, the shell is essentially hollow. If this shell originally was filled with gas at a density equal to the average density for the molecular cloud core, $n(H_2) = 1.3 \times 10^4\,cm^{-3}$ (Reipurth *et al.* 1986), then the mass that has been cleared from this cavity is on the order of $0.1\,M_\odot$. There are at least two reasons that this cavity could not be cleared by a counterjet with properties similar to the known HH 34 jet.

First, the HH 34 jet is very well confined and has a diameter of only 0.″7 (10% of the diameter of the hollow shell) over almost its entire length. Second, the mass-loss rate of the optical jet is only $2 \times 10^{-9}\,M_\odot\,yr^{-1}$, which is insufficient to clear $0.1\,M_\odot$ gas in less than 10^5 yr(Reipurth *et al.* 1986). This time is much longer than the kinematical time scale of the jet, 800 yr, and comparable to typical kinematical time scales of bipolar CO flows.

However, if there were a wind present, such as the neutral wind which drives the CO outflow in HH 7-11, with a mass loss rate of a few times $10^{-6}\,M_\odot/yr$ (Lizano *et al.*1988), then the cavity could be swept out on the order of 10^3–10^4 yr. In addition, most bipolar CO flows are not very well collimated, having length-to-width ratios on the order of 1–6; a typical ratio for the HH 7-11 outflow is 2, implying an opening angle of 60° (Snell & Edwards 1981). Thus, such an outflow would have no trouble clearing out the observed cavity.

QUESTIONS

Hasegawa-san: Do you have any explanation for the HCO^+ line wing being single-sided rather than symmetric?
Answer: No. The correlator setup used was biased toward blueshifted gas, so this may be an instrumental effect, but Lizano *et al.* (1988) also found high-velocity HCO^+ around HH 7-11, only blueshifted.
Kwok-san: In my opinion the problem of momentum flux is completely exaggerated. In the paper of Kwok & Volk (1988), we were able to show that the observed high-velocity parameters can be easily explained in an energy-conserving model.
Answer: As an observer, I try never to tie my observations to a particular model. In the case of L1551, I have found a source of the momentum flux driving the CO flow, whether it is needed or not.

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