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ON THE ENERGETICS OF HIGH-VELOCITY MOLECULAR FLOWS[1]

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ABSTRACT

The paradox of excessive momentum observed in high-velocity flows near star-formation regions compared to the available photon momentum can be resolved by a model of adiabatic interaction between a stellar wind and the circumstellar molecular cloud. It is shown that the momentum of the swept-up material can be raised two orders of magnitude if the expansion of the swept-up shell is due to thermal pressure from a hot-shocked stellar wind. We conclude that many of the observed properties of high-velocity flows are consistent with the hypothesis that the flows are driven by radiation pressure from the central star. It is suggested that the molecular cloud density distribution necessary to explain the high-velocity flow has a form of $\rho \propto r^{-3/2}$.

Subject headings: interstellar: molecules — shock waves — stars: formation — stars: mass loss

I. INTRODUCTION

The discovery of high-velocity flows near star-formation regions has generated new interest in the study of the star-formation process. These flows were first discovered by the observation of extended wings of the CO $J = 1 \rightarrow 0$ rotational line (Zuckerman, Kuiper, and Rodriguez-Kuiper 1976). Mapping of the high-velocity emission regions suggests an anisotropic angular distribution of the redshifted and blueshifted components (Bally and Lada 1983). Centers of these molecular flows often coincide with strong sources of infrared emission which may represent sites of recent star formation (Downes *et al.* 1981). Since such flows have been observed in both high-mass (e.g., Orion) and low-mass (e.g., T Tauri stars) star-formation sites, they may correspond to a universal evolutionary stage between the collapse of the parent molecular cloud and the eventual formation of new stars.

The amount of mass contained in the outflow can be estimated from the antenna temperature of the molecular line, and the velocity of the flow can be measured from the extent of the line wings. The derived high values for both the mass and velocity of the flow suggest that it is a very energetic phenomenon. It has been emphasized by a number of authors that the observed momentum in the flow exceeds the photon momentum in the central source by several orders of magnitude, and therefore the flows cannot be driven by radiation pressure of the central star (Genzel and Downes 1982; Bally and Lada 1983).

However, a closer examination of the physical situation suggests that a more detailed analysis of the flow dynamics is needed before any conclusion can be drawn about the energetics of the flows. First, the observed high-velocity flows are often embedded in molecular clouds, and it is possible that part of the observed mass in the flow is due to swept-up, rather than ejected, material (Bally and Lada 1983; Snell *et al.* 1984). Second, although the observed flow velocities are high compared to the local sound speed, they are low compared to the escape velocity of the central star. This suggests that the flow has been significantly decelerated since its ejection from the star. Third, there is empirical evidence that the larger flow sources have lower velocities, which again points to deceleration (Fig. 19 of Bally and Lada 1983). Fourth, while the observed flow momentum seems to exceed the photon momentum, the mechanical luminosity is only a small fraction of the luminosity of the central star.

The above four points suggest that the observed high-velocity flows are the results of the interaction of a heretofore unobserved stellar wind with the circumstellar molecular clouds. It is therefore inappropriate to compare the momentum of the flow to that of the radiation field, and the mechanism of driving the flow can be understood only when we have gained some knowledge of the stellar wind. Specifically, if the stellar wind–molecular cloud interaction is energy-conserving, the momentum of the molecular flow can be greater than that in the wind. The interaction of a steady stellar wind with a uniform-density medium was calculated by Castor, McCray, and Weaver (1975) and Weaver *et al.* (1977) for the case of interstellar bubbles, and their model is applied to the molecular outflow case by Beckwith, Natta, and Salpeter (1983). Wind interaction with an ambient medium with density distribution $\rho \propto r^{-2}$ is discussed in the context of planetary nebulae by Kwok, Purton, and Fitzgerald (1978), Kwok (1983, 1984), and Kahn (1983). In this paper we shall generalize the wind interaction model to nonuniform density distributions and discuss whether the existing observational data are compatible with the molecular flow being driven by radiation pressure.

II. THE MODEL

Let us assume that the high-velocity flow is centered on a star of luminosity L_* embedded in a molecular cloud with density distribution of the form $\rho(r) = \rho_0(r/r_0)^{\beta}$. A stellar wind is then ejected from the star at time $t = 0$ with a steady mass loss rate of $\dot{m}$ and velocity v. When the wind encounters the circumstellar material, a shock front will be generated and begin to sweep up the ambient gas. This shock front is likely to be isothermal, and a high-density shell will be built up at the interface. At the same time a reverse shock propagates toward the star, and the stellar wind will gradually be shocked to high temperature. For simplicity, we assume the shell to be thin and consist of only swept-up circumstellar material. In this case, we can assume the shocked stellar wind to be separated from the

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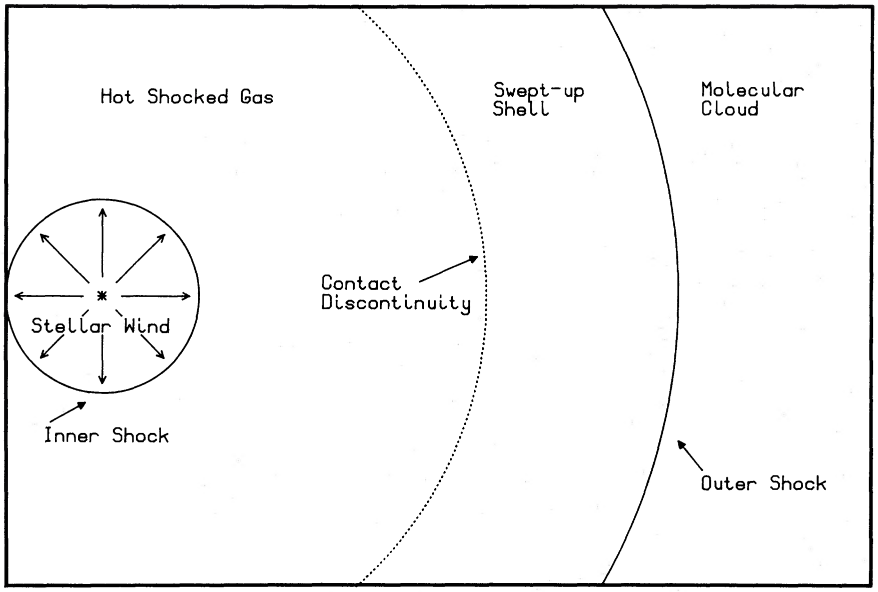

FIG. 1.—Schematic diagram of the wind interaction model

shell by a contact discontinuity (at radius R_s from the star), and the expansion of the shell to be due to thermal pressure of the hot region. A schematic diagram of the model is shown in Figure 1.

Assuming radiative loss to be negligible, we have from the conservation of mass, momentum, and energy the following equations:

$$\frac{dM_s}{dt} = 4\pi R_s^2 \rho V_s \,, \tag{1}$$

$$\frac{d}{dt}(M_s V_s) = 4\pi R_s^2 P \,, \tag{2}$$

$$\frac{d}{dt}(2\pi R_s^3 P) = \frac{1}{2}\dot{m}v^2 - 4\pi R_s^2 P V_s \,, \tag{3}$$

where $V_s = dR_s/dt$, M_s is the mass of the swept-up shell, and P is the pressure in the hot region.

Combination of equations (1), (2), and (3) leads to a third-order nonlinear differential equation which cannot be solved analytically. We have adopted the method of similarity analysis, which provides the following asymptotic solutions:

$$R_s(t) = [C\dot{m}v^2(\rho_0 r_0^{-\beta})^{-1} t^3]^{1/(\beta+5)} \,, \tag{4}$$

$$V_s(t) = \frac{3}{\beta+5}\frac{R_s(t)}{t} \,, \tag{5}$$

$$M_s(t) = \frac{4\pi}{\beta+3}[C\dot{m}v^2(\rho_0 r_0^{-\beta})^{2/(\beta+3)} t^3]^{(\beta+3)/(\beta+5)} \,, \tag{6}$$

$$P(t) = \frac{3(2\beta+7)}{(\beta+3)(\beta+5)^2} \times [C\dot{m}v^2(\rho_0 r_0^{-\beta})^{3/(\beta+2)} t^{-(\beta-4)/(\beta+2)}]^{(\beta+2)/(\beta+5)} \,, \tag{7}$$

where $C = (\beta+3)(\beta+5)^3/[12\pi(2\beta+7)(\beta+11)]$ and $\beta \neq -3$, -4, -5, $-7/2$, or -11.

In order to study the energetics of the problem, we define two parameters π and ϵ, which are the ratios of the shell to wind momentum and energy respectively. Specifically,

$$\pi = \frac{M_s V_s}{\dot{m}vt} \tag{8}$$

and

$$\epsilon = \frac{1/2 M_s V_s^2}{1/2 \dot{m}v^2 t} \,. \tag{9}$$

Substituting equations (4)–(6) into equation (9), we have

$$\epsilon = \frac{3(\beta+5)}{(2\beta+7)(\beta+11)} \,, \tag{10}$$

which is independent of time. Table 1 lists the values of ϵ for several values of β, and we can see that the efficiency of converting wind energy to shell energy increases with increasing density gradient in the ambient gas.

The momentum efficiency π, however, is generally a function of t:

$$\pi = \frac{12\pi}{(\beta+3)(\beta+5)}[C^{\beta+4}\dot{m}^{-1}v^{\beta+3}(\rho_0 r_0^{-\beta})t^{\beta+2}]^{1/(\beta+5)} \,. \tag{11}$$

Only in the case $\beta = -2$ is π a constant. Expressed in astronomical units,

$$\pi = 41.3\left\{\frac{[n_{H_2}(1\ \text{pc})/10^3\ \text{cm}^{-3}](v/1000\ \text{km s}^{-1})}{(\dot{m}/10^{-6}\ M_\odot\ \text{yr}^{-1})}\right\}^{1/3} \tag{12}$$

for $\beta = -2$.

TABLE 1

EFFICIENCY IN CONVERTING WIND TO SHELL ENERGY

β	ϵ
0	0.19
−1	0.24
−1.5	0.28
−2	0.33

We can see that for an energy-conserving interaction, the shell momentum can be many times the wind momentum. To decide whether radiation pressure is the responsible mechanism, one has to compare $\dot{m}v$ to L_*/c, but not the observed shell momentum.

III. COMPARISON WITH OBSERVATIONS

There are a number of problems in the interpretation of observational data. The observed molecular emission is contaminated by emission from the molecular cloud, which contribution has to be subtracted before one can estimate the mass in the flow. Also, one cannot use the maximum width of the line wings as V_s because most of the mass (as indicated by the antenna temperature) moves at speeds less than the maximum value. Furthermore, there is the complication of projection effects. Although the age of the flow is often identified with the dynamical age (R_s/V_s), this is true only if V_s is constant.

The best flow parameters derived from observations are those of Snell *et al.* (1984), who obtain estimates of M_s, V_s, and R_s for four star-formation regions. We shall adopt their observational results as basis for comparison with our model.

There are four free parameters in the model, namely, β, $L_w = 1/2\dot{m}v^2$, ρ_0, and t, to fit three observed parameters, M_s, V_s, and R_s. One might also wish to impose the condition that the wind momentum not exceed the photon momentum, or $\dot{m}v \leq L_*/c$. In this case, $\dot{m}$ and v have to be considered as independent parameters. We are not entirely free to choose any values of the model parameters, however. For example, we expect v to be several times the surface escape velocity of the central star (Abbott 1978; Heap 1982), which implies that v should be $\sim 10^3$ km s^{-1}. Self-similar solutions to the gravitational collapse of molecular clouds show that $\beta \approx -3/2$ in the inner region and $\beta \approx -2$ for the outer envelope (Shu 1977). Values of ρ_0 are also restricted because of observational constraints imposed by CO emission in the molecular cloud.

Because of the large uncertainties in the flow parameters and in the estimates of the bolometric luminosities of the central stars, we feel that it is not justified to seek a mathematical best fit to the observations. Instead, we have tried a number of examples using physically reasonable model parameters. Table 2 shows four models for the $\beta = -3/2$ case and their comparisons with the observed parameters of GL 490, NGC 2071, S140, and Orion. In spite of this limited effort, we can see that all four examples of outflow can be reasonably fitted by the model and the problem of momentum inadequacy no longer exists.

IV. DISCUSSION

We have demonstrated that the wind interaction model can explain the existing observations of molecular flows; but are there other predictions that would allow it to be tested? We have postulated a high-speed stellar wind from the central star which has not yet been observed. In fact, it can be shown that the shock front is located very near to the star, and most of the region interior to R_s is in fact made up of hot shocked gas. In this case, the density in the hot region is approximately given by

$$\rho_{\mathrm{HG}} = \frac{\dot{m}t}{4/3\pi R_s^3} . \tag{13}$$

Substituting equations (7) and (13) into the ideal gas law, the temperature of the shocked region is given by

$$T = \left(\frac{\beta + 5}{\beta + 11}\right) \frac{\mu m_{\mathrm{H}} v^2}{3k} , \tag{14}$$

where μ is the mean atomic weight, k is the Boltzmann constant, and m_{H} is the mass of the hydrogen atom. Equation (14) shows that the efficiency of converting kinetic energy to heat decreases with increasing $|\beta|$. This is because for higher values of $|\beta|$ a larger fraction of the energy goes into the expansion of the shell (see Table 1).

For a fully ionized gas, $\mu \approx 0.6$, the predicted temperature of the hot region is

$$T = 2.4 \times 10^7 \left(\frac{\beta + 5}{\beta + 11}\right)\left(\frac{v}{1000 \text{ km s}^{-1}}\right)^2 \text{ K} . \tag{15}$$

Because of the high temperature, the radiative cooling rate is very low. Levreault (1983) finds a high cooling rate by assuming a low temperature ($< 10^5$ K) in the shocked region. But the conduction front which is needed to cool the gas to 10^5 K develops over a period of $\sim 10^6$ yr (Weaver *et al.* 1977) and is not relevant to the young objects being considered here. We can therefore conclude that the adiabatic assumption is an appropriate one.

X-ray emission is also expected from this hot region. Assuming that thermal bremsstrahlung is the dominant emission mechanism, the predicted X-ray flux between 0.2 and 4 keV (which corresponds to the energy range of the imaging proportional counter [IPC] of the *Einstein* satellite) is

$$S(0.2\text{–}4 \text{ keV}) = \frac{5.44 \times 10^{-39}}{D^2} T^{-1/2} \int n_e n_i dV \times \int_{0.2 \text{ keV}/h}^{4 \text{ keV}/h} g_\nu(T) e^{-h\nu/kT} d\nu , \tag{16}$$

where h is the Planck's constant and the Gaunt factor $g_\nu(T) = (4.8 \times 10^{-11}\nu/T)^{-0.4}$.

The X-ray flux densities expected from a sphere of radius R_s (using parameters in Table 2) are given in Table 3. Since the flows do not occupy 4π radians, the observed fluxes should be less than the numbers in Table 3. Effects of interstellar extinction would further reduce the observed fluxes.

Results shown in Table 3 suggest that only the Orion high-velocity flow is likely to be detected by the IPC. An X-ray source of $6.9 \pm 0.29 \times 10^{-12}$ ergs cm^{-2} s^{-1} is found in the Trapezium region by Ku and Chanan (1979). Observations using the high-resolution imager on the *Einstein Observatory* locate a source of 2.1×10^{-13} ergs cm^{-2} s^{-1} (No. 20, Ku, Righini-Cohen and Simon 1981) which is within the error box for the center of bipolar CO emission (Snell *et al.* 1984). These results are not inconsistent with the predicted values when the effects of extinction and geometry are considered.

So far we have not addressed the problem of collimation, i.e., how the outflow is concentrated into two opposite directions. One possibility is that the density distribution of the molecular cloud is not spherically symmetric when the density increases toward the equatorial directions. The resultant flow would expand much faster along the direction of least resistance, the polar directions. The energetics of this problem would not be greatly different from the spherically symmetric case, however.

TABLE 2
MODEL PARAMETERS AND RESULTS

	PARAMETERS				MODEL RESULTS					OBSERVED VALUES[a]			
OBJECT	$\dot{m}$ $(M_\odot \text{ yr}^{-1})$	v (km s^{-1})	$n_{H_2}(r = 1 \text{ pc})$ (cm^{-3})	t (10^3 yr)	M_s $(M_\odot)$	V_s (km s^{-1})	R_s (pc)	π	$\dot{m}v/(L_*/c)$	M_s $(M_\odot)$	V_s (km s^{-1})	R_s (pc)	L_* $(L_\odot)$
GL 490	10^{-8}	4000	500	17	13.9	7.4	0.15	150	0.5–4.6	15.4	8.6	0.15	4.3×10^2–3.9×10^3
NGC 2071	10^{-8}	2000	400	23	9.9	5.1	0.14	109	1.0	9.7	8.4	0.14	10^3
S 140	10^{-7}	2000	1000	13	21.6	8.2	0.13	68	0.1–0.7	24.4	7.1	0.11	1.4×10^4–10^5
Orion	10^{-6}	2000	400	1.5	8.0	14.4	0.026	38	1.0	8.2	19.5	0.03	10^5

[a] From Snell *et al.* 1984.

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TABLE 3

MODEL PREDICTED TEMPERATURES AND X-RAY FLUXES

Object	T (10^7 K)	D (pc)	S(0.2–4 keV) (10^{-12} ergs cm^{-2} s^{-1})
GL 490	15	500–1500	< 0.0023–0.021
NGC 2071	3.7	500	< 0.037
S 140	3.7	910	< 0.48
Orion	3.7	500	< 240

V. CONCLUSIONS

We have postulated that the high-velocity molecular flows near star-formation regions do not directly originate from the stars but represent material swept up by a shock generated by the interaction of a stellar wind with the circumstellar molecular cloud. If this interaction is adiabatic, then the momentum in the swept-up shell can increase by a hundredfold over the wind momentum. We find in the four examples of high-velocity flows where good observed parameters are available that the observations are consistent with the radiation pressure being the driving mechanism if winds of velocities greater than 10^3 km s^{-1} are generated by the central stars. This model can be tested by the direct detection of such high-speed winds or the observation of X-ray emission in the shocked region.

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