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JET-ACCELERATED MOLECULAR OUTFLOWS: THE MASS-VELOCITY AND INTENSITY-VELOCITY RELATIONS

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RESUMEN

Utilizamos simulaciones numéricas para aclarar las relaciones masa-velocidad e intensidad-velocidad para flujos de chorros. Los perfiles de CO simulados reproducen las leyes de potencia quebradas observadas en los flujos moleculares sorprendentemente bien, sin necesidad de dos regimenes de arrastre. Se propone un modelo analítico para explicar el exponente $\simeq -1.5$ de la relación masa-velocidad suave subyacente.

ABSTRACT

We use numerical simulations to clarify the mass-velocity and intensity-velocity relations for jet-driven outflows. The simulated CO profiles reproduce the broken power laws observed of molecular outflows remarkably well, with no need for two distinct entrainment regimes. An analytic model is proposed to explain the exponent $\simeq -1.5$ of the underlying smooth mass-velocity relation.

Key Words: **ISM: JETS AND OUTFLOWS — STARS: MASS LOSS — STARS: PRE-MAIN SEQUENCE**

1. INTRODUCTION

Various authors have noted that the intensity-velocity relationship observed in low-J CO lines in molecular outflows tends to follow a broken power law $I_{\rm CO}(v) \propto v^{-\gamma}$, with $\gamma \approx 1.8 \pm 0.5$ up to line-of-sight velocities $v_{\rm break} \approx 10$ to $30\,{\rm km\,s^{-1}}$ and $\gamma \approx 3$ to 7 at higher velocities (e.g., Rodríguez et al. 1982; Stahler 1994; Bachiller & Tafalla 1999; Richer et al. 2000). This property is an important test for proposed mechanisms of molecular outflow acceleration. In particular, recent work has addressed this issue in the case of entrainment by a jet.

Using an analytic model of a jet/bowshock system, Zhang & Zheng (1997) predicted a mass distribution following a broken power law, $m(v) \propto v^{-\mu}$, with slopes $\mu \approx 1.8$ up to $10\,{\rm km\,s^{-1}}$ and $\mu \approx 5.6$ beyond. The CO intensity profiles are reproduced if the CO abundance and line excitation do not vary much with velocity. However, this seems unlikely given the broad range of shock strengths in a bowshock.

Smith, Suttner, & Yorke (1997) conducted numerical simulations of jet-driven molecular outflows that take into account dissociation and heating in shocks. They find that $I_{\rm CO}(v)$ follows a power law $v^{-\gamma}$ with $\gamma \approx 1.2$ to 1.6 up to $10\,{\rm km\,s^{-1}}$, and a steeper slope further out, in agreement with observations. They attribute this result to a much steeper $m(v) \propto v^{-3.5}$ than Zhang & Zheng (1997). However, their reasoning involves an erroneous high temperature-dependence of the CO emissivity ($\propto T$ instead of T^{-1}). Therefore, the actual origin of the slope of $I_{\rm CO}(v)$ in jet simulations, and the underlying $m(v)$, remain to be clearly established. In this work, we clarify this issue using simulations at higher resolution, and analytical modeling.

2. NUMERICAL MODEL

The simulations presented in this work are performed in 2-D cylindrical symmetry. The densities of molecular and atomic hydrogen are tracked, along with the ionization fraction of hydrogen. The CO density is assumed to be a constant (10^{-4}) fraction of the H_2 density by number. The numerical scheme is a Godunov scheme which is second order in time and space (see e.g., Downes & Ray 1999).

The grid-spacing was set at 10^{14} cm. The jet radius was 5×10^{15} cm, and its density was $100\,{\rm cm^{-3}}$ (equal to the ambient density), thus allowing a resolution of cooling layers a factor of 10^2 to 10^4 higher than in Smith et al. (1997). The time-averaged jet velocity was $215\,{\rm km\,s^{-1}}$. Superimposed on this were sinusoidal variations with periods of 5, 10, 20 and 50 years and a total amplitude of 60%. Using smaller amplitudes did not affect any of our results.

3. RESULTS

3.1. *The Mass-Velocity and Intensity-Velocity Relations*

Figure 1 displays a grayscale plot of the total number density in our jet simulation at $t = 400$ yr. Figure 2 contains plots of various mass-velocity and

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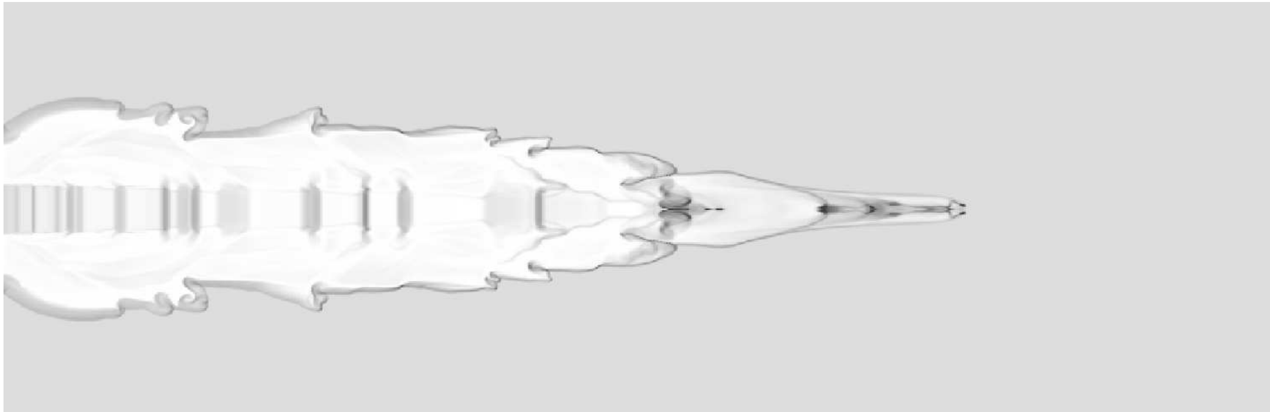

Fig. 1. Grayscale plot of the total number density at $t = 400\,\mathrm{yr}$. The logarithmic scale ranges from 7.1×10^{-25} to $1.4 \times 10^{-18}\,\mathrm{g\,cm^{-3}}$.

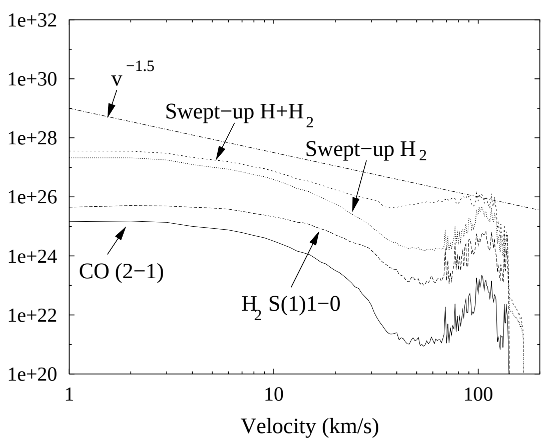

Fig. 2. Plots of the mass-velocity relations for all swept-up material, $m(v)$, and for molecular swept-up material only, at $t = 400\,\mathrm{yr}$. Also shown are the intensity-velocity relations for the CO $J = 2$–1 line and for the $\mathrm{H_2}$ $S(1)$ 1–0 line (arbitrary offsets). An angle of 30° to the plane of the sky is assumed.

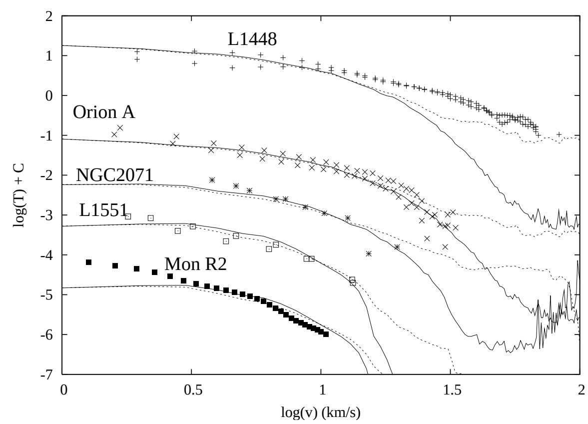

Fig. 3. Plots of the observed intensity-velocity relations (from Bachiller & Tafalla 1999) together with simulation results for the $m(v)$ (dotted line) and $I_{\mathrm{CO}}(v)$ (solid line) relations. The viewing angle assumed is 60° to the plane of the sky for the comparison with L 1448 and Orion A, 30° for NGC 2071, and 0° for L 1551 and Mon R2. The plots have been adjusted in the vertical direction to allow easy comparison of the shapes of the relations.

intensity-velocity relations for the same simulation, assuming an angle of 30° to the plane of the sky. It is found that the total swept-up mass $m(v)$ (excluding jet material) follows roughly a power-law relation with exponent $\mu \simeq -1.5$. This agrees with the low-velocity slope in the analytical model of Zhang & Zheng (1997), but their predicted break at higher velocity is not seen.

The mass-velocity relation for swept-up *molecular* material ($m_{\mathrm{H_2}}(v)$) does, however, show a steepening at higher velocities ($v \geq 20\,\mathrm{km\,s^{-1}}$). This steepening occurs because, at higher velocities, material has been through a stronger shock and hence a greater fraction of molecules has been dissociated.

If we now consider the $I_{\mathrm{CO}}(v)$ relation we can see that, while at low velocities it is qualitatively similar to the $m(v)$ relation, at higher velocities it steepens even more than $m_{\mathrm{H_2}}(v)$. This results from the temperature dependence of the line emission. When T exceeds the excitation energy of the upper level, the line emissivity varies as T^{-1}, due to the partition function (see, e.g., Cabrit & Bertout 1990). Hence, as we go to higher velocities, not only do we have fewer molecules available to emit (due to dissociation) but they emit less intensely in the $J = 2$–1 line once the post-shock temperature exceeds $\simeq 40\,\mathrm{K}$.

3.2. *Comparison with Observations*

Figure 3 shows plots of the observed $I_{\mathrm{CO}}(v)$ relations for five outflows (from Tafalla & Bachiller 1999). Also plotted are the mass-velocity and

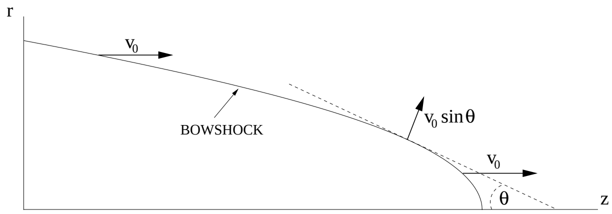

Fig. 4. Diagram of the setup for the analytic model.

intensity-velocity relations from the simulation in Fig. 1. It can be seen that the simulation results for the $I_{\rm CO}(v)$ relation reproduce the observations remarkably well, bearing in mind the lack of tuning here (the ages and densities in the simulation, for example, are not similar to those in the physical systems). It is also interesting to note that the predicted $I_{\rm CO}(v)$ more closely matches the observations than the total mass-velocity relation $m(v)$, except for L 1448.

4. ANALYTIC MODEL

Consider an idealized bowshock surface given by the relation $z \propto r^s$ (see Figure 4). If there is no mixing, the magnitude of the post-shock velocity in the observer's frame is $v_0 \sin\theta$, with $\theta = \arctan(dr/dz)$ defined in Fig. 4. An observer along the z-axis will then see a line-of-sight velocity $v = v_0 \sin^2\theta$. Far from the apex, when θ is small, $\sin\theta \approx \tan\theta$ and the rate of increase of mass at velocity v is

$$\frac{d}{dt}\left(m(v)dv\right) = \rho_{\rm a} v_0 2\pi r(v)\, dr \propto (v)^{s/(1-s)}\, dv. \quad (1)$$

Hence the mass-velocity relation in this case is a power law $m(v) \propto v^{-\mu}$ with $\mu = s/(s-1)$.

We can estimate an effective value for s in our simulation by calculating the expected rate of sweep-up of mass by the bowshock. If $r_{\rm max}$ is the maximum radius at time t, when the bowshock length is $z = v_0 t$,

$$\frac{dm(t)}{dt} = \rho_{\rm a} v_0 \pi r_{\rm max}^2(t) = \rho_{\rm a} v_0 \pi \left(v_0 t\right)^{2/s}. \quad (2)$$

By plotting $m(t)$ as a function of t in our simulation we find that $s \simeq 2.5$ to 2.8. This yields $\mu \simeq 1.55$ to 1.66, in excellent agreement with our simulations.

Smith et al. (1997) evaluated a similar model, but assuming instantaneous mixing of post-shock ambient gas. They obtain an exponent $\mu = 2 + s/2$, ranging between 3 and 3.5 for our value of s. This is much steeper than the $m(v)$ in our simulations.

5. CONCLUSIONS

We find that the $m(v)$ relation in jet-driven molecular outflow is a power law of exponent $\simeq -1.5$, with no break at higher velocity. The $m(v)$ relation agrees with a simple bowshock model with no mixing, rather than with full mixing.

The intensity-velocity relation for CO (2–1) *does* have a break in slope around 10 to $20\,{\rm km\,s^{-1}}$, and compares remarkably well with observations. The break results from molecular dissociation near the apex, and from the $1/T$ dependence of emission at temperatures exceeding the energy of the upper level of the line. Because of this dependence on T, our model predicts a shallower slope at high velocity in higher excitation lines (e.g., H_2 $S(1)$ 1–0 and high-J CO lines), which could be tested by ongoing studies.

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