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ENTRAINMENT IN HERBIG-HARO OBJECTS

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RESUMEN

Este artículo da primero una reseña de la literatura sobre la incorporación de material molecular a los jets HH. Los modelos disponibles en principio pueden reproducir la emisión de H_2 de un número de objetos HH. Sin embargo, hay algunos jets HH con nudos alineados que muestran estructuras básicamente idénticas en la emisión de lineas de H_2 y de átomos y/o iones. Para estos objetos, sugerimos una posible explicación en términos de la ablación de material molecular de nudos densos inmersos dentro del haz del jet.

ABSTRACT

This paper first reviews the literature of entrainment of molecular material into HH jets. The available models can, in principle, reproduce the H_2 emission of a number of HH objects. However, there are some HH jets with aligned knots which show basically identical structures in the H_2 and atomic/ionic line emission. For these objects, we suggest a possible interpretation in terms of the ablation of molecular gas from dense clumps which are immersed within the jet beam.

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

1. INTRODUCTION

It has long been suggested that the molecular emission associated with Herbig-Haro (HH) jets might come from molecular environmental gas which has been entrained into a high velocity, atomic/ionic flow.

Following the paper of Kahn (1980), models based on a "mixing length", turbulent viscosity approach have been developed by a number of authors. Analytic and numerical models of plane and cylindrical mixing layers and cylindrical, turbulent flows have been studied by Cantó & Raga (1991), Richer, Hills, & Padman (1992), Raga et al. (1993), Malone, Dyson, & Hartquist (1994), Stahler (1994), Lizano & Giovanardi (1995), Dyson et al. (1995), Taylor & Raga (1995), Noriega-Crespo et al. (1996), Rawlings & Hartquist (1997) and Binette et al. (1999), with approaches ranging from purely analytic, isothermal treatments to numerical models including more or less detailed treatments of the chemical and/or ionic processes. Time-dependent, axisymmetric numerical simulations with a detailed, parallel chemistry were carried out by Lim, Rawlings, & Williams (1999).

The other possibility that has been studied in some detail is that the molecular gas corresponds to environmental material which has been entrained in either the leading working surface of the jet, or in "internal working surfaces" resulting from a time-variability in the ejection velocity. This process has been curiously named "prompt entrainment" in the astrophysical literature, as opposed to "head entrainment" in the "normal" jet literature.

Analytic models of this process have been presented by Masson & Chernin (1993) and Raga & Cabrit (1993), and Raga, Cabrit, & Cantó (1995) presented a hybrid working surface/turbulent jet model. Numerical simulations (with varying degrees in the sophistication of the chemistry) of this process have been carried out by Chernin et al. (1994), Raga et al. (1995), Downes & Ray (1999), and Lim, Rawlings, & Williams (2001a). Lim et al. (2002) have studied the production of H_2 emission by accelerating working surfaces (see also Lim 2003). Suttner et al. (1997), Smith, Suttner, & Yorke (1997) and Völker et al. (1999) have presented models of molecular jets moving in a molecular environment, in which "head entrainment" is also taking place (although in these models at least part of the molecular emission comes from the jet material). There are also several papers which present models and comparisons with observations of "molecular bowshocks" (which we do not reference here).

Let us now concentrate on the infrared H_2 emission of HH jets. Some objects (such as HH 46/47, see e.g., Fernandes 2000) show emission that appears to be mostly associated with the larger bowshock structures of the jet, which can be interpreted (at least in a qualitative way) with "molecular bowshock" models.

At least one object, HH 110, shows molecular emission along the jet beam, but with a clear offset to one side of the optical (atomic and ionic)

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emission (Davis, Mundt, & Eislöffel 1994; Noriega-Crespo et al. 1996). This object has been interpreted and modeled as the result of the collision of an HH jet with the surface of a dense cloud (Reipurth, Raga, & Heathcote 1996; Raga & Cantó 1995; de Gouveia Dal Pino 1999; Hurka, Schmid-Burgk, & Hardee 1999), and it has been speculated that the molecular emission could come from the dense cloud molecular material that has been ablated by the jet. Raga et al. (2002) have recently presented numerical simulations with the relevant chemical/physical processes that show that this interpretation is possibly correct, since the computed models show optical atomic/ionic and infrared H_2 emission that resembles HH 110 in a quite striking way.

We are then left with a few objects which show atomic/ionic and H_2 emission with basically identical "aligned knot" morphologies. An example of this kind of situation is illustrated by HH 111 (Gredel & Reipurth 1993, 1994; Reipurth et al. 1999).

The most striking example of outflows with similar atomic/H_2 aligned knot structures is the HH 1 jet. Reipurth et al. (2000) have obtained H_2 1–0 S(1), [Fe II] 1.64 μm and [S II] 6717/30 Å images of this jet with the *Hubble Space Telescope* (*HST*), and find that the molecular and ionic emission have very similar spatial distributions. In particular, they have obtained the deconvolved FWHM of the cross section of the jet as a function of position, and find that the same widths (within the measurement errors) are obtained for the three observed emission lines. This result appears to be difficult to reproduce with "entrained molecular gas" models, as in all of these models (at least, in the ones that have been published up to now) the molecular emission is distributed in an outer, more or less cylindrical structure surrounding the atomic/ionic jet beam.

A possible way for obtaining such coincident H_2 and atomic (or ionic) emission structures is, of course, to assume that the jet is initially at least partially molecular, as has been done (see above) by Suttner et al. (1997), Smith et al. (1997) and Völker et al. (1999). Unfortunately, the only available models of molecule formation in outflows from young stars (Rawlings, Williams, & Cantó 1988; Glassgold, Mamon, & Huggins 1989) suggest that for mass-loss rates suitable for HH objects, a substantial molecular fraction is not attained. However, this result should be re-analyzed in the light of more modern, jet-like outflow models, which might give a more favourable result.

In this paper we follow a different possibility. Redman & Dyson (1999) suggested that jet-like features in planetary nebulae might correspond to a collimated flow which is mass loading off small, dense clumps which have survived the passage of the jet head, and are now embedded within the jet beam. If dense, molecular clumps were to be found embedded within the beam of HH jets, the ablated molecular material could, in principle, fill in the jet beam. In this way, similar molecular and atomic/ionic emission line morphologies might be produced.

2. THE INTERACTION OF HH JETS WITH DENSE, MOLECULAR CLUMPS

Let us consider a dense, homogeneous clump of density ρ_c and radius r_c which is immersed in the beam of a jet of density ρ_j, velocity v_j and radius r_j. The shock induced within the clump by the interaction with the jet has a velocity

$$v_c \approx \sqrt{\frac{\rho_j}{\rho_c}}\, v_j \; . \tag{1}$$

If we assume that all of the shocked clump material is entrained into the jet flow, the mass supply rate of clump material $\dot{M}_c$ is given by the relation

$$\frac{\dot{M}_c}{\dot{M}_j} \approx \left(\frac{r_c}{r_j}\right)^2 \sqrt{\frac{\rho_c}{\rho_j}} \, , \tag{2}$$

where $\dot{M}_j = \pi {r_j}^2 \rho_j v_j$ is the mass-loss rate of the jet flow.

The time t_c for which the jet/clump interaction lasts is given by

$$t_c \approx \frac{2r_c}{v_c} \approx \frac{2r_j}{v_j}\left(\frac{r_j}{r_c}\right)\frac{\dot{M}_c}{\dot{M}_j} \; , \tag{3}$$

where the second equality is obtained using equations (1) to (2).

Now, in order to have a non-negligible contribution of molecular mass entrained from the clump into the jet, we would need to have at least $\dot{M}_c/\dot{M}_j \sim 10^{-3}$. Also, in order for the jet/clump interaction to last for a substantial fraction of the dynamical lifetime t_{dyn} of the jet, we would need to have $t_c \approx t_{dyn} \sim 1000\,$yr. Considering as typical values $r_j \approx 3 \times 10^{15}\,$cm and $v_j \approx 200\,\mathrm{km\,s^{-1}}$, from equation (3) we then obtain $r_c/r_j \approx 10^{-5}$. Inserting these values in equation (2) we then obtain $\rho_c/\rho_j = 10^{14}$.

Assuming that the jet has a $n_j = 10^4\,\mathrm{cm^{-3}}$ number density, we then conclude that the clump has a $M_c \approx 10^{-7}\,M_\odot$. On the other hand, if we want the clump to supply a higher contribution of molecular material to the mass flux of the jet of $\dot{M}_c/\dot{M}_j \sim 0.1$, we would need a clump of mass $M_c \approx 10^{-4}\,M_\odot$.

From this discussion we conclude that in order to have clumps which

- contribute a non-negligible molecular mass to the mass flux of the jet,
- last for a time comparable to the dynamical timescale of the jet,

then they need to have a mass of the order of 10^{-4} to 0.1 times the mass of a giant planet.

It is, of course, not unreasonable to think that condensations with these kinds of masses might be present in the surroundings of young stars. However, it is not clear that they would be found in the region through which the jet is travelling, which is thought to lie parallel to the axis of the angular momentum of the star+disk system.

In order to study the properties of jets which are mass loading material from molecular clumps, one would then have to consider the mass-loading wind formalism developed by John Dyson and collaborators (see e.g., Dyson & Hartquist 1987; Charnley et al. 1988; Pittard, Hartquist, & Dyson 2001). Also, the details of the clump ablation process (which are necessary for determining the mass-loading rate) have been studied by Dyson, Hartquist, & Biro (1993), and most recently by Lim, Rawlings, & Williams (2001b). The ablation of stratified clumps has been studied by Arthur & Lizano (1997).

3. INTERACTIONS WITH MOVING CLUMPS

If we have dense clumps which have a peculiar motion with respect to the jet source, the clumps could penetrate the jet from one side, and in this way inject molecular material into the jet beam. This possibility has the attractive property that even low-mass clumps (which would be incorporated into the jet in a very short timescale) would be able to modify the chemical composition of the jet beam (instead of having an effect only in the region close to the leading working surface, as would be the case for a stationary clump).

If the clumps have a typical velocity $v_{\rm p}$, a fraction of the clumps inside a cylinder of radius

$$r_{\rm p} \approx r_{\rm j} + v_{\rm p} t_{\rm dyn} \sim r_{\rm j} + 3 \times 10^{15}\, v_1 t_{1000}\,{\rm cm}, \qquad (4)$$

would be able to interact with the jet beam ($v_1 = v_{\rm p}/1\,{\rm km\,s^{-1}}$, $t_{1000} = t_{\rm dyn}/1000\,{\rm yr}$). In other words, if the clumps have $v_{\rm p} \sim 1\,{\rm km\,s^{-1}}$ (typical of turbulent motions within a molecular cloud), they would have to be within ~ 200 AU from the outflow axis in order to be able to interact with the jet beam.

Figure 1 shows the results of a 3-D numerical simulation of the base of an HH jet, and the interacion of the jet with a moving clump. In this simulation, an atomic jet with an initial velocity $v_{\rm j} = 200\,{\rm km\,s^{-1}}$, number density $n_{\rm j} = 10^3\,{\rm cm^{-3}}$, temperature $T_{\rm j} = 10^3\,{\rm K}$ and radius $r_{\rm j} = 10^{14}\,{\rm cm}$, travels along the z-axis into a homogeneous, neutral environment of density $n_{\rm env} = 100\,{\rm cm^{-3}}$ and temperature $T_{\rm env} = 10^3\,{\rm K}$. An initially homogeneous, spherical, molecular clump of radius $r_{\rm c} = 10^{14}\,{\rm cm}$, number density (of atomic nuclei) $n_{\rm c} = 10^6\,{\rm cm^{-3}}$ and temperature $T_{\rm c} = 10\,{\rm K}$ travels in the $+x$-direction at a $v_p = 30\,{\rm km\,s^{-1}}$ velocity, and hits the jet with a $y = 5 \times 10^{13}\,{\rm cm}$ impact parameter. The simulation was carried out with the version of the "yguazú-a" code described by Raga et al. (2002), using a 5-level adaptive grid with a maximum resolution of $1.56 \times 10^{13}\,{\rm cm}$ (along the three axes) and a computational domain of $(2, 2, 4) \times 10^{15}\,{\rm cm}$ along the x-, y- and z-axes (respectively).

From the time-sequence shown in Figure 1, it is clear that the jet/moving clump interaction results in a substantial amount of molecular material being entrained into the jet beam. The interacion of a jet with several of such moving clumps could therefore result in the introduction of more or less smoothly distributed molecular gas into an HH flow.

4. CONCLUSIONS

We have discussed the work that has been done in the past regarding the entrainment of molecular material into HH jets. Some HH jets show H_2 emission, which is distributed either off-axis with respect to the atomic/ionic emission, or in the main bowshocks of the flows. The H_2 emission of these objects can be explained (at least in a qualitative way) in terms of models in which an atomic/ionic jet entrains gas from a surrounding, molecular environment.

On the other hand, some HH objects show H_2 emission that coincides with the chains of aligned emitting knots that are observed in the atomic/ionic emission lines. These objects are more difficult to explain in terms of an "entrained molecular gas" model.

For these objects, we suggest the possibility that the molecular gas might be coming from the interaction of the jet with dense, molecular clumps which are immersed within the jet beam. A possible problem of this model is that in order for the clumps to survive over the lifetime of the jet (so that they would still be injecting molecular material at the time at which we are observing the outflows), they have to have masses of the order of the mass of a giant planet.

Clumps with smaller masses would inject molecular material into the jet beam only for short timescales. A possible way to reconcile such short

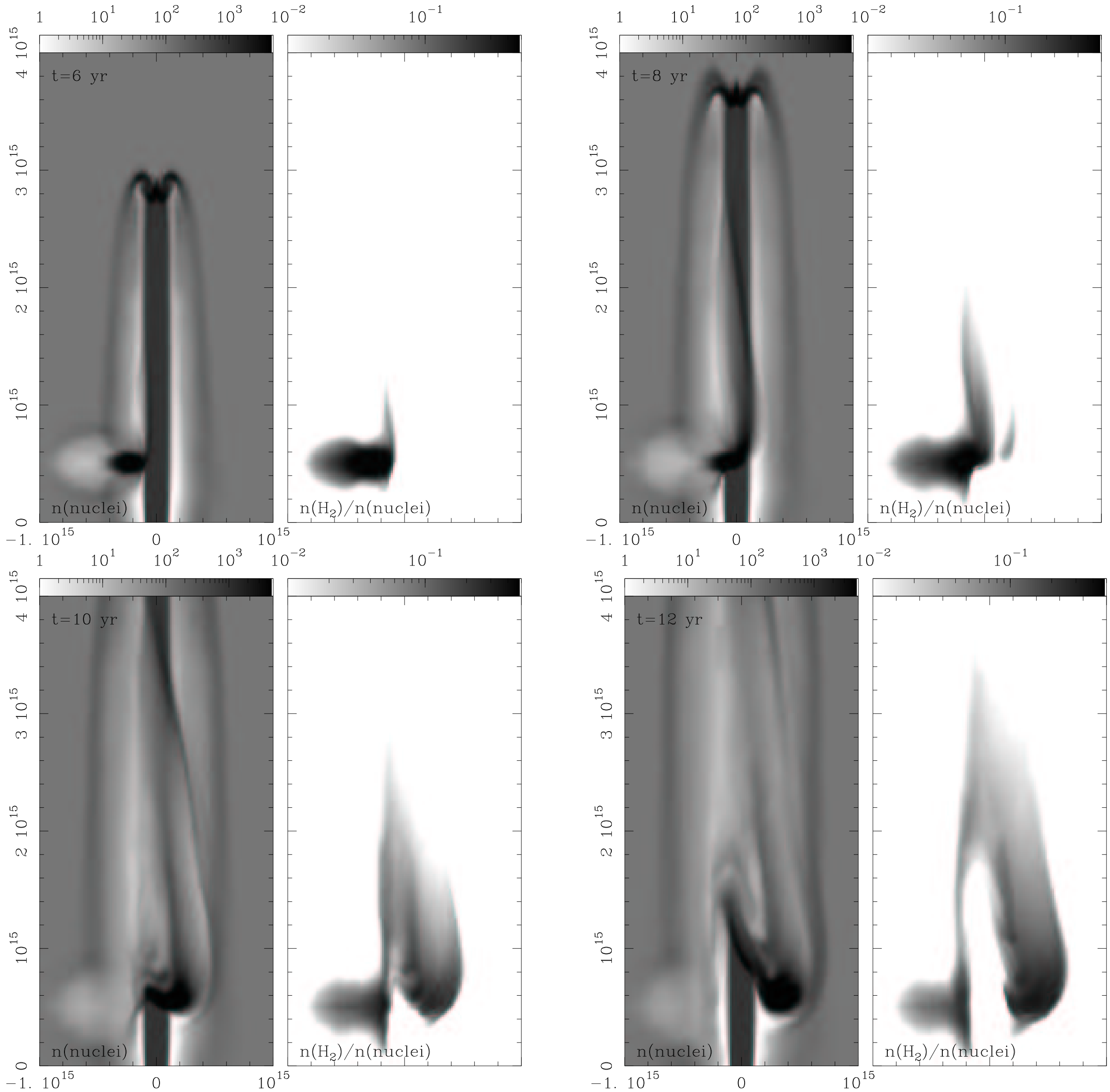

Fig. 1. Time sequence showing the jet/moving clump model described in the text. Each time frame (with the time in years shown on the density plot) shows the number density of atomic nuclei and the molecular fraction, depicted with the logarithmic greyscales given by the bars on top of each graph (in cm^{-3} units for the number density). The stratifications correspond to cuts along the $y = 0$ plane, and the x- and z-axes are labeled in cm.

timescales with the lifetime of the jet would be to have a large number of "moving clumps", which penetrate the jet beam from one side, and inject (at least part of) their molecular material into the jet flow. This is an interesting possibility that might deserve future study.

We end by pointing out that the observations of objects like the HH 1 jet (Reipurth et al. 2000) show a spatial coincidence between the molecular and the atomic/ionic emission that appears to be too extreme for the models of entrained clumps we have presented in this paper. In terms of our models, in order to reproduce the observed emission we would need to have a large number of very small clumps, so as to produce a smooth mixing between the molecular and the atomic/ionic material. Also, the fact that we do not observe any direct evidence for the occurrence of jet/clump interactions or even for the existence of clumps with appropriate properties is somewhat discouraging.

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