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# 3D SPH SIMULATIONS OF GIANT HERBIG-HARO FLOWS AND JET-CLOUD INTERACTIONS IN STAR FORMATION REGIONS

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## RESUMEN

Describimos algunos resultados recientes de simulaciones tridimensionales con hidrodinámica de partículas suavizadas (SPH) de chorros densos con enfriamiento radiativo en regiones de formación estelar. Discutimos la estructura y cinemática de los objetos HH gigantes recientemente detectados y la interacción de chorros HH con las nubes densas y compactas que los rodean.

## ABSTRACT

We review some recent results of three-dimensional smoothed particle hydrodynamics (SPH) simulations of overdense, radiatively cooling jets in star forming regions. We discuss the structure and kinematics of the recently detected giant HH flows and also the interaction of HH jets with dense, compact clouds of the ambient medium.

*Key Words:* **HYDRODYNAMICS — ISM: JETS AND OUTFLOWS — METHODS: NUMERICAL**

It has been recently discovered that several Herbig-Haro (HH) jets observed in star forming regions, which were previously believed to have typical lengths of $\sim 0.1$ pc are, in fact, rather long and possess a chain of approximately regularly spaced bright internal bow-shaped knots that may extend over several parsecs away from the source (e.g., the HH 34 and HH 111 systems: Devine et al. 1997; Reipurth, Bally, & Devine 1997). These so called giant HH flows promise to alter significantly our conception of the young stars and the nature of their interaction with the environment. In particular, a detailed measurement of the kinematic structure of the HH 34 system has revealed that both the radial velocities and proper motions of the internal bow-shocks decrease smoothly and systematically on either side of the source (with the radial velocities dropping from $\sim 190$ to 50 km s$^{-1}$ in $\sim 1.5$ pc). Is this deceleration due to impact with the ambient medium or to an intrinsic aspect of the flow? We here address this question by examining the dynamical structure and evolution of giant HH flows with the help of 3D SPH simulations (de Gouveia Dal Pino & Stahler 2000, hereafter GS2000). In the second part of this short review, we also briefly discuss recent numerical results of jet interactions with ambient compact, dense clouds (de Gouveia Dal Pino 1999).

To carry out the simulations, we have employed a modified version of the SPH code originally developed by de Gouveia Dal Pino & Benz (1993, 1994; see also Cerqueira, de Gouveia Dal Pino, & Herant 1997; Cerqueira & de Gouveia Dal Pino 1999 for an MHD version of the code). In order to match the observed conditions in the giant HH flows, we have assumed an overdense, radiative cooling jet that is injected into the ambient medium with a long-period and large-amplitude velocity variation with a sinusoidal profile at injection (see Fig. 1) The jet in Figure 1 has propagated $\sim 0.5$ pc for $\sim 2500$ yr. A chain of multiple bow shocks has developed due to the oscillating input velocity (GS2000). The initial sinusoidal profile has steepened into a saw-tooth pattern as faster gas has caught up with slower gas. Moreover, the peak velocities are falling with distance (by a factor $\sim 2$ within 0.5 pc), as is the velocity of propagation of the internal pulses, which is in good agreement with the observed kinematics of HH 34 system. This result, although preliminary, suggests that jet deceleration can be naturally explained by oscillating jets with large-amplitude velocity variability propagating into a warm medium. The jet is being slowed down by the impact with the ambient gas and momentum is being taken up by expelled jet material sideways, mostly behind the bow shocks (GS2000). For a similar interpretation for the

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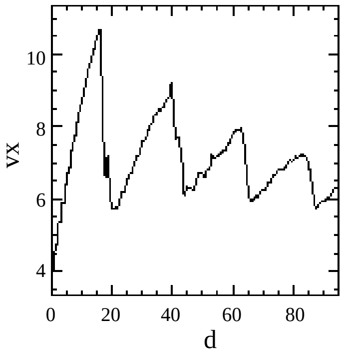

Fig. 1. Velocity profile along the jet axis for a sinusoidal velocity variation at injection with a period $P \simeq 764$ yr, velocity amplitude $\Delta v = 100$ km s$^{-1}$, and maximum jet velocity $v_{j,max} = 200$ km s$^{-1}$. The initial density ratio between the jet and the ambient medium is $\eta = n_j/n_a = 3$, $n_a = 200$ cm$^{-3}$, $v_x$ is in units of the ambient sound speed, $c_a$ =16.6 km s$^{-1}$, and the distance is in units of the jet radius $R_j = 10^{16}$ cm (from de Gouveia Dal Pino & Stahler 2000).

jet deceleration see also Cabrit & Raga (2000).

Jets in star forming regions propagate through a complex ambient medium with dense cores and clumps and may eventually collide with them. As a classical example, in the HH 270/HH 110 system observed by Reipurth, Raga, & Heathcote (1996), HH 110 seems to be the deflected part of the HH 270 jet that, according to the authors' interpretation, has impacted with an invisible cloud. Our recent results of fully 3D SPH simulations of jet-cloud interactions strongly support this interpretation (de Gouveia Dal Pino 1999). Furthermore, the interaction produces important transient and permanent effects on both the jet and the cloud. As an example of these transient effects, Figure 2 shows the results of an off-axis collision of a jet with a dense cloud with a radius twice as large as the jet radius, and a central density about 300 times larger than that of the jet. A poorly collimated deflected beam develops with a complex knotty structure which is very similar to that observed in the deflected beam of the HH 270/HH 110 system. Later, when the incident beam has penetrated most of the cloud extension, the deflected beam fades and the jet resumes its original direction of propagation (de Gouveia Dal Pino 1999).

Because of the assumed small size of the interacting clouds ($R_c = 1$ to $2$ $R_j$), the lifetime of the examined interactions is very small, $\sim$ few 10 to 100 yr and, therefore, not easy to observe, but they may leave important permanent signatures too, in the surviving outflow. In particular, the left-overs of the cloud and deflected beam are deposited into the working surface thus contributing to the enrichment of its knotty structure. Further, a jet undergoing many transient interactions with compact clumps along its propagation and lifetime may inject a considerable amount of shocked jet material sideways into the ambient medium, hence providing a powerful tool for momentum deposition into the surrounding molecular flow. For the simulation of Figure 2, we find that a mass and momentum rate $\dot{M} \simeq 2 \times 10^{-8} M_\odot$ yr$^{-1}$, and $\dot{P} \simeq 4 \times 10^{-6} M_\odot$ yr$^{-1}$ km s$^{-1}$, respectively, are transferred sideways per interaction, during the jet lifetime.

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Astrophysical Plasmas: Codes, Models, and Observations (Mexico City, 25-29 October 1999)
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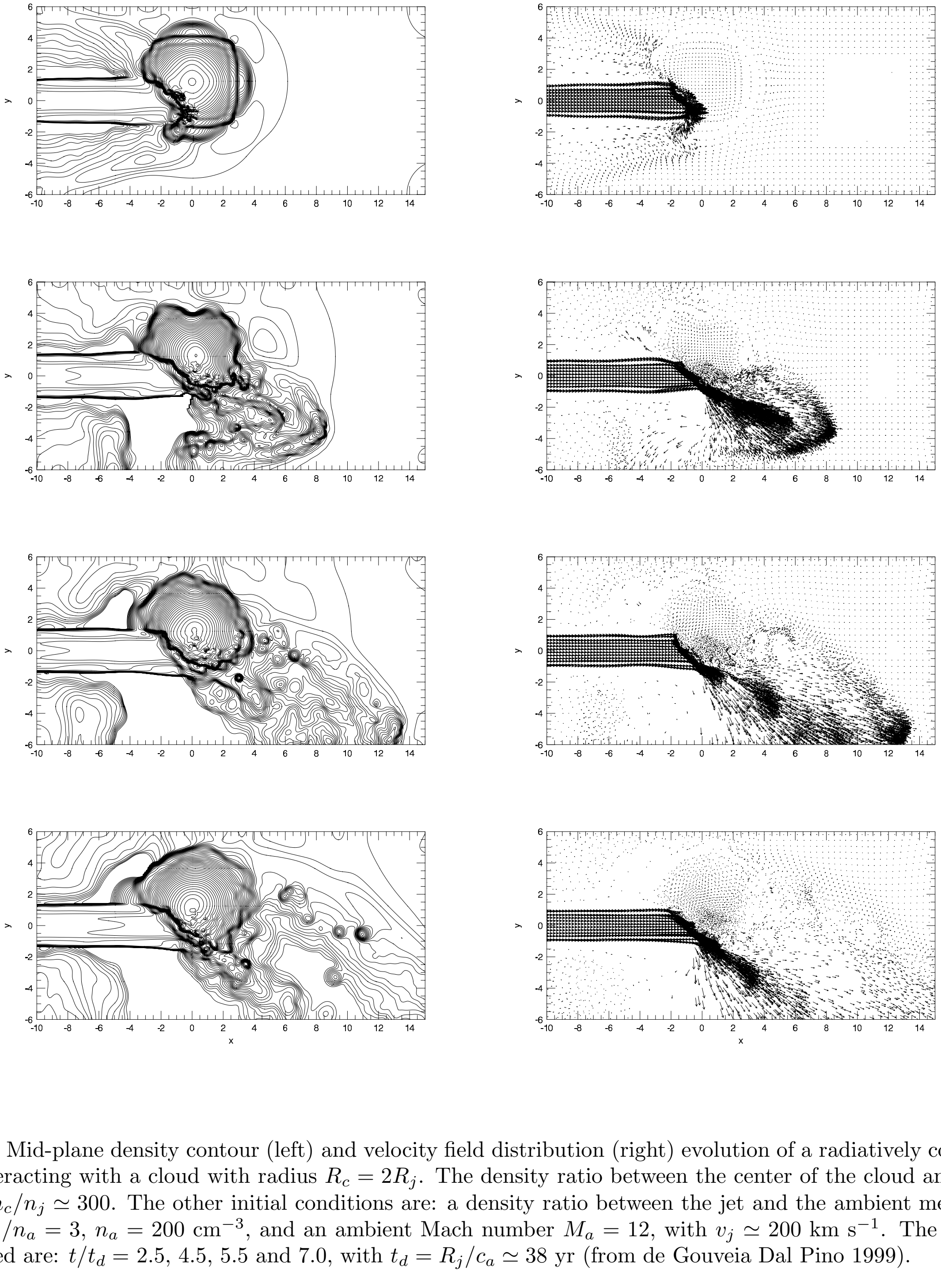

Fig. 2. Mid-plane density contour (left) and velocity field distribution (right) evolution of a radiatively cooling jet interacting with a cloud with radius $R_c = 2R_j$. The density ratio between the center of the cloud and the jet is $n_c/n_j \simeq 300$. The other initial conditions are: a density ratio between the jet and the ambient medium $\eta = n_j/n_a = 3$, $n_a = 200$ cm$^{-3}$, and an ambient Mach number $M_a = 12$, with $v_j \simeq 200$ km s$^{-1}$. The times depicted are: $t/t_d = 2.5$, 4.5, 5.5 and 7.0, with $t_d = R_j/c_a \simeq 38$ yr (from de Gouveia Dal Pino 1999).