Jet-Cloud Interactions in Star Forming Regions

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1. Introduction

I here summarize the results of three-dimensional smoothed particle hydrodynamics (SPH) simulations of interactions of overdense, radiatively cooling and adiabatic jets with dense, compact clouds in frontal and off-axis collisions. Calculated for a set of parameters which are particularly appropriate to protostellar jets our results indicate that the interaction produces important transient and permanent effects in the jet morphology.

The basic characteristics of the SPH numerical technique here employed, the assumed initial conditions,and the results are described in detail by de Gouveia Dal Pino (1999). As an example, Figure 1 shows the results of an off-axis collision for a radiatively cooling jet with Mach number $M_a = 12$, a jet to cloud density ratio $\beta = (n_j/n_c)^{1/2} = 0.04$, and a cloud radius $R_c = R_j$.

In off-axis interactions, the deflected beam initially describes a C-shaped trajectory around the curved jet/cloud contact discontinuity but the deflection angle tends to decrease with time as the beam slowly penetrates the cloud. Later, when the jet has penetrated most of the cloud extension the deflected beam fades and the jet tends to resume its original direction of propagation. During the interaction, a weak chain of internal knots develops along the deflected beam. Clouds with different density parameter, β, result different deflection angles and interacting times - the larger the density of the cloud the larger the angle, and the longer the interaction time. The increase of R_c also makes the deflection angle and the interaction time larger, while the increase in the incident jet Mach number, M_a, naturally decreases the interaction time. The average velocity of the deflected beam is consistent with the predicted value $v_{jd} \approx v_j \cos\theta$, where θ is the deflection angle (e.g., Canto et al. 1988). The impact also decreases the beam collimation. This morphology and kinematics is very similar to that observed in candidate systems like HH270/HH110. Our simulations also reveal the formation of a *head-neck* bright structure at the region of impact that resembles the morphology of the HH110 knot A, located in the apex of the HH110 jet, where the deflection is believed to occur. All these similarities strongly support the proposed jet/cloud interaction interpretation for this system (Reipurth et al. 1996). The fact that the deflection angles derived from the simulations are smaller than that observed and the fact that the jet/cloud interaction is still taking place indicate that the interacting cloud in that system must have a radius $R_c >> R_j$, as previously suggested (Reipurth et al 1996), and $\beta = (n_j/n_c)^{1/2} \leq 0.1$.

Due to the small size of the clouds ($R_c \approx R_j$), the interactions examined here are very transient (with lifetimes ~10-100 yr which are << than the dynamical lifetimes of the protostellar outflows, $\tau \geq 10^4$ yr). Nonetheless, they leave important signatures in the surviving outflow. The left-overs of the cloud and the knots that are produced in the deflected beam are deposited into the working surface and contribute to enrich the knotty pattern commonly observed in HH objects.

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 surrounding ambient medium and this process may provide a powerful tool for momentum transfer and turbulent mixing with the ambient medium.

Figure 1. Mid-plane density contour (left) and velocity field distribution (right) evolution of a radiative cooling jet-cloud interaction for a system with $\beta = 0.04$, $M_a = v_j/c_a = 12$ (with $v_j \approx 200$ km/s); jet radius

R_j = 2 10^{15} cm; cloud central coordinates (0, 1.2 R_j, 0); and initial jet to ambient density ratio $\eta = n_j/n_a$ = 3, with n_a = 200 cm^{-3}. The times depicted are t/t_d = 2.0, 3.0, 4.0, 5.0, and 6.5 ($t_d = R_j / c_a$ = 38 yr). The distances are in units of R_j = 2 x10^{15} cm. The density lines are separated by a factor of 1.3 in the 2nd and 3rd panels, and 1.2 in the rest. The maximum density in the contours is 5x10^3 n_a (see de Gouveia Dal Pino 1999, for details).

References

de Gouveia Dal Pino, E.M. 1999, ApJ (in press) (astro-ph/9904145)
Reipurth, B., Raga, A.C. & Heathcote S. 1996, A&A, 311, 989