THREE-DIMENSIONAL SIMULATIONS OF JET/CLOUD INTERACTIONS: STRUCTURE AND KINEMATICS OF THE DEFLECTED JETS

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Received: April 99; accepted: June 1999

to appear in The Astrophysical Journal

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ABSTRACT

We report the results of three-dimensional smoothed particle hydrodynamics 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.

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 resumes its original direction of propagation. During the interaction, a weak chain of internal knots develops along the deflected beam and the velocity field initially has a complex structure that later evolves to a more uniform distribution. The average velocity of the deflected beam is consistent with the predicted value given by \( v'_j \approx v_j \cos \theta \) (where \( \theta \) is the deflection angle, and \( v_j \) is the velocity of the incident beam). The impact also decreases the beam collimation. Applied to the context of the protostellar jets, this morphology and kinematics found for the deflected beam is very similar to that observed in some candidate systems like the HH 110 jet which has been previously proposed to be the deflected part of the HH270 jet. Our simulations also reveal the formation of a head – neck bright structure at the region of impact which resembles the morphology of the HH 110 knot A located in the apex of the HH 110 jet where the deflection is believed to occur. All these similarities strongly support the proposed jet/cloud interaction interpretation for this system. 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 $R_c \gg R_j$, where $R_j$ is the jet radius, as previously suggested, and a density ratio between the jet and the cloud $\beta^2 = n_j/n_c \lesssim 10^{-2}$.

Due to the small size of the clouds [with radius $R_c \simeq (1-2)R_j$], the interactions examined here are very transient (with lifetimes of few $\sim 10$ to $\sim 100$ yr which are $\ll$ than the typical dynamical lifetimes of the protostellar outflows, $\tau \gtrsim 10^4$ 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 behind the bow shocks of protostellar jets. Also, the collision may partially destroy the shell at the head producing remarkable asymmetries in the head region. 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.

*Subject headings:* Stars: pre-main-sequence - stars: mass loss - ISM: jets and outflows - clouds - hydrodynamics
1. Introduction

The collimated, highly supersonic Herbig-Haro (HH) jets that emerge from protostars in star forming regions propagate through a complex ambient medium composed of many dense cloud cores and may eventually collide with some of these objects. Although these outflows are usually observed to propagate away from their sources in approximately straight lines (see e.g., Reipurth 1997 for a recent review on protostellar outflows), there are some cases where the outflow is observed to be deflected. Among these, there are some examples, like HH 270/110 (Reipurth et al. 1996, Rodriguez et al. 1998), HH 30 (López et al. 1995), and the molecular outflow in L 1221 (Umemoto et al. 1991) in which the deflection seems unlikely to be caused by peculiar changes in the direction of motion of the central source. Particularly in the first case, there seems to be strong evidence that the jet deflection is caused by the encounter with a dense cloud.

Previous analytical and numerical work was performed to investigate the hydrodynamics of interactions of shock-fronts and supersonic winds with interstellar clouds (see, e.g., McKee & Cowie 1975, Rozyczka & Tenorio-Tagle 1987, Klein, McKee, & Colella 1994, Xu & Stone 1995, Raga et al. 1998), but all those studies have focused on the effects of the interaction on the structure of the cloud. The problem of the interaction of an astrophysical jet with a rigid surface has been investigated analytically with some detail by Canto, Tenorio-Tagle & Rozyczka (1988, hereafter CTR). In the context of extragalactic jets, the well known correlation and spatial alignment between radio and optical structures in extended extragalactic radio-sources and Seyfert galaxies (e.g., McCarthy et al. 1987, Viegas & de Gouveia Dal Pino 1992) have led to a series of analytical and numerical studies involving the interaction of light jets with ambient clouds (e.g., Higgins at al. 1995, Fedorenko & Courvoisier 1996, Steffen et al. 1997).

In the context of radiatively cooling, heavy jets (i.e., denser than their surroundings)
a picture believed to be consistent with protostellar jets, the problem of jet/cloud encounters and their effects on the jet structure has been discussed by Raga & Canto (1995) who focused in the early stages of the interaction using a simple analytical model and two-dimensional simulations involving slab jets impacting a large, flat surface of high density at an arbitrary angle of incidence. Subsequently, Canto & Raga (1996) and Raga & Canto (1996) have discussed a steady-state solution based on Bernoulli’s theorem for adiabatic and radiatively cooling jets penetrating into a cloud with a plane-parallel pressure stratification with exponential profile (Canto & Raga 1996) and a spherically symmetric pressure stratification with power-law profile (Raga & Canto 1996). Also, de Gouveia Dal Pino, Birkinshaw & Benz (1996; hereafter GBB96) and de Gouveia Dal Pino & Birkinshaw (1996; hereafter GB96) have examined numerically the structure and evolution of jets normally propagating through stratified environments with different power-law pressure distributions.

In the present work, with the help of fully three-dimensional simulations (which naturally retain sensitivity to asymmetric effects) we attempt to extend these prior studies by examining the structure and evolution of radiatively cooling and adiabatic jets undergoing frontal and off-axis collisions with compact clouds of finite density. Although the typical sizes of the cloud cores in star forming regions are usually much higher than the jet radius \( R_j \), with the assumption here of more compact clumps (with radius \( R_c \gtrsim R_j \)) we are able to follow the whole evolution of the interacting system and the deflected beam (whose lifetime time must not much exceed the time it takes for the shock that develops with the impact to travel over the cloud diameter). Besides, with this assumption we can more realistically examine, for example, the effects of the impact of a beam with the edges of an ambient cloud in an off-axis collision, and also the effects of the curvature of the cloud in the beam deflection – effects that are clearly absent in plane-parallel analyses.
In §2 of this paper, we outline the numerical method and the initial conditions. In §3, we present the results of the simulations, and in §4 we address the conclusions and the possible implications of our results for protostellar jets.

2. The Numerical Model and Setup

To simulate the jet/cloud interactions, we have employed a modified version of our three-dimensional hydrodynamical code based on the smoothed particle hydrodynamics (SPH) technique (de Gouveia Dal Pino & Benz 1993; see also Benz, 1990, 1991, Monaghan 1992, and Steinmetz & Mueller 1993 for an overview of the method and a discussion of the capabilities and limitations of the SPH). SPH is a Lagrangean, gridless approach to fluid dynamics in which particles track the flow and move with it. The code solves the hydrodynamics equations of continuity, momentum, and energy explicitly in time, in Cartesian coordinates. Originally developed to investigate interactions between planets and planatesimals (e.g., Benz, Cameron, & Melosh 1989), and stellar encounters (e.g., Benz, Bowers, Cameron, & Press 1990, Davies, Benz, & Hills 1992), the code was successively implemented to study supernova explosions (e.g., Herant, Benz, & Colgate 1992), and the structure and evolution of overdense jets propagating into initially homogeneous ambient media (de Gouveia Dal Pino & Benz 1993, hereafter GB93). The later version was subsequently modified to investigate pulsed jets (de Gouveia Dal Pino & Benz 1994, hereafter GB94); molecular outflows and related processes of momentum transfer between the jet and the molecular environment (Chernin, Masson, de Gouveia Dal Pino, & Benz 1994); jet propagation into stratified environments in star formation regions (GBB96 and GB96); and more recently, the effects of magnetic fields on the structure of overdense radiatively cooling jets (e.g., Cerqueira, de Gouveia Dal Pino, & Herant 1997, Cerqueira & de Gouveia Dal Pino 1999, hereafter CG99).
A series of validation tests of the code and direct comparisons with results of standard Eulerian, grid-based calculations in two and three-dimensions were successfully performed – our SPH calculations produce similar results to those of grid-based schemes, even considering a small number of particles, although the spatial resolution may be inferior (with the production of smoother interfaces) due to intrinsic numerical diffusion (GB93, GB94, Chernin et al. 1994, GB96, CG99, Benz 1990; see also Davies et al. 1993 for a detailed comparison of SPH calculations with those produced by different finite-difference methods).

In the present work, we have modified the pure hydrodynamical version of the code above (see GB93 and GB96) by introducing a cloud in the homogeneous ambient domain. Following is a short summary of the key features of the code that are relevant to this work (for more detailed discussion of the basic assumptions see the references above).

The computational domain is a 3-D rectangular box which represents the ambient medium and has dimensions $-16R_j \leq x \leq 16R_j$, $-6R_j \leq y,z \leq 6R_j$, where $R_j$ is the initial jet radius (and $R_j$ is the code distance unit). The Cartesian coordinate system has its origin at the center of the box and the jet flows through the x-axis, and is continuously injected into the bottom of the box [at $\vec{r} = (-16R_j,0,0)$]. Inside the box, the particles are initially distributed on a Cartesian grid. Outflow boundary conditions are assumed for the boundaries of the box (GB96).

The particles are smoothed out by a spherically symmetric kernel function of width $h$. As in previous work (GB93, GB94, GB96, CG99), the initial resolution, as characterized by the initial value of $h$, was chosen to be $0.4R_j$ and $0.2R_j$ for the ambient, and the jet and cloud particles (see below), respectively. With this initial particle spacing, the calculations are started with about 74,000 particles. Former validation tests (e.g., GB93) have shown that the above choice of initial values of $h$ is more than appropriate to reveal (with accuracy
and reasonably good definition) the physical properties of the structure of overdense jets.
(The decrease of these initial values by a factor two, for example, enormously increase the
number of particles in the system and thus the required amount of computer time and space,
without significant improvement to the resolution.) During the evolution of the flow, \( h \) is
consistently allowed to vary (Benz et al. 1990) and the resolution is naturally established
by the particle distribution — high-density regions (like shock zones) have higher resolution
because of the larger concentration of particles, while low-density regions (like the cocoon
that envelopes the beam) retain a lower resolution (see below). (For a discussion on the
basic criteria to monitor accuracy in our SPH code and also in SPH schemes in general, see
also Benz 1990, 1991, Monaghan 1992, and references therein.)

As in previous work, the jet, the cloud, and the ambient gas are treated as a fully
ionized fluid with an adiabatic index \( \gamma = 5/3 \) and an ideal equation of state. The radiative
cooling, which is due to collisional excitation and recombination, is implicitly calculated
using a time-independent cooling function for a gas of cosmic abundances cooling from
\( T \simeq 10^6 \) to \( 10^4 \) K (the cooling is set to zero for \( T < 10^4 \) K; see GB93, GB96). The time
integration is done using a second order Runge-Kutta-Fehlberg integrator. The shock waves
which arise in the flow are handled by the usual Newmann-Ritchmyer artificial viscosity
and a link-list method is used to find the particle’s neighbors (e.g., Monaghan 1992).

An initially isothermal cloud with a Gaussian density (and pressure) profile

\[
n_{cl} = n_a + n_c \exp \left( -\left( r-r_c \right)^2 / \sigma^2 \right), \tag{1}
\]

is placed near the center of the computational domain, where \( n_a \) is the ambient number
density, \( n_c \) is the number density in the center of the cloud, \( r_c^2 = x_c^2 + y_c^2 + z_c^2 \) is its central
coordinate, and \( \sigma \) is the width of the Gaussian profile which we assume to be \( \sigma = 0.75 \) \( R_c \)
in all the simulations, where \( R_c \) is the initial radius of the cloud. For simplicity, the initial
temperature of the cloud is assumed to be the same as that of the surrounding ambient
medium \((T_{cl} = T_a)\).

During the simulations, the cloud is held steady by the application of an appropriate gravitational potential upon its particles. Similarly to previous studies of jet propagation in stratified environments (Hardee et al. 1992, GBB96, GB96), this external potential is simply evaluated by assuming that the cloud is initially in hydrostatic equilibrium so that \(\vec{\nabla} p_{cl} = \rho_{cl} \vec{g} \), where \(p_{cl} = n_{cl} K T_a\) is the thermal pressure in the cloud, \(\rho_{cl} = \bar{m} n_{cl}\) is the mass density, and \(\vec{g}\) is the gravitational acceleration. Substituting eq. (1) into the equation above and performing the derivation, it yields

\[
\vec{g} = -\frac{2 K T_a}{\bar{m} \sigma^2} (\vec{r} - \vec{r}_c^0) \frac{n_c \exp\left(-\frac{(\vec{r} - \vec{r}_c)^2}{\sigma^2}\right)}{n_a + n_c \exp\left(-\frac{(\vec{r} - \vec{r}_c)^2}{\sigma^2}\right)}
\]

where \(\bar{m} \approx 0.5 m_H\) is the mean mass per particle, \(m_H\) is the hydrogen mass, and \(K\) is the Boltzmann constant.

Since in the SPH scheme it is trivial to distinguish between particles in the jet and those in the ambient medium or in the cloud, it is easy to have the external force above computed only over the cloud particles, and once a particle is swept from the cloud by the impinging jet this force is no longer computed on it. During the jet/cloud interaction, this force becomes negligible with respect to the impact forces. Its effects on the jet dynamics are also negligible since the jet is assumed to be highly supersonic (see below).

The models are parameterized by the dimensionless numbers: \(\text{i})\) the density ratio between the jet and the ambient medium, \(\eta = n_j/n_a\); \(\text{ii})\) the ambient Mach number, \(M_a = v_j/c_a\) (where \(v_j\) is the jet velocity and \(c_a\) is the ambient sound speed); \(\text{iii})\) the jet to the ambient medium pressure ratio at the jet inlet, \(\kappa = p_j/p_a\), that we assume to be equal to unit; \(\text{iv})\) the square root of the density ratio between the jet and the center of the cloud \(\beta = (n_j/n_c)^{1/2}\) (see, e.g., Canto & Raga 1995); \(\text{v})\) the ratio between the cloud and the jet radius \(R_c/R_j\); and \(\text{vi})\) the ratio of the cooling length in the post-shocked gas behind the
bow shock to the jet radius $q_{bs} = d_{cool}/R_j$ (see, e.g., GB93).

The major advantages and limitations of our SPH calculations have been addressed in previous work (GB93, Chernin et al. 1994, GB96); in particular, two points should be remarked. Firstly, as we mentioned above, the properties of low-density regions are more poorly sampled because they do not contain as many particles as a denser region. However, not having to calculate properties of empty regions is actually one of the advantages of SPH codes over fixed grid based codes. Secondly, turbulent effects which should exist in these flows (since the expected Reynolds numbers are very high, $Re > 10^4$; GB93), are more difficult to examine because the numerical viscosity of the code may be too dissipative and the initial particle spacing is large relative to the size of the eddies that may develop in the flow ($\sim d_{cool}/Re < R_j/10^4$). Thus, for this work, we can only consider the bulk properties of the jet/cloud interaction, i.e., over a size scale larger than that of most of the eddies, at which the internal turbulent motions are averaged out.

3. The Simulations

We have carried out a series of numerical experiments of jet/cloud encounters involving clouds with $R_c = (1 - 2)R_j$ and initial jet/cloud density parameter $\beta \simeq 3.5 \times 10^{-2} - 2 \times 10^{-1}$. The parameters of the simulations were chosen to resemble typical conditions found in protostellar jets and their environment. We have adopted an initial number density ratio between the jet and the ambient medium $\eta = n_j/n_a = 3$, $n_j = 600$ cm$^{-3}$, ambient Mach numbers $M_a = v_j/c_a = 12 - 24$ (with $v_j \simeq 200 - 400$ km s$^{-1}$ and $c_a = (\gamma KT_a/\bar{m})^{1/2} \simeq 16.6$ km s$^{-1}$ is the ambient sound speed), and $R_j = 2 \times 10^{15}$ cm. The corresponding initial jet Mach numbers are numbers $M_j = v_j/c_j \simeq 20.8 - 41.7$ and $c_j = (\gamma KT_j/\bar{m})^{1/2} = c_a/(\eta)^{1/2} \simeq 9.6$ km s$^{-1}$ (this last condition on $c_j$ is due to the assumed pressure equilibrium at the jet inlet; see §2).
The paragraphs below present the results of the simulations performed for both off-axis and frontal collisions involving radiatively cooling and adiabatic jets, and Table 1 summarizes the values of the input parameters.

### 3.1. Radiatively Cooling Jet/Cloud Off-Axis Interactions

Figure 1 shows the results of a jet/cloud off-axis interaction in the x-y plane. It depicts the density contour in the mid-plane section and the velocity field distribution evolution of a radiatively cooling jet which impacts a dense cloud with an initial radius $R_c = R_j$, central coordinates $(0, 1.2 R_j, 0)$, and a square root of the jet to central cloud density ratio $\beta \approx 4 \times 10^{-2}$. The incident jet has initial $\eta = 3$ and ambient Mach number $M_a = 12$ (see Table 1), and the cloud has central coordinates $(0, 1.2 R_j, 0)$.

We find that a double shock pattern develops in the region of impact at $t/t_d = 2.0$ (where $t_d = R_j/c_a \simeq 38$ yr corresponds to the transverse jet dynamical time). The incident beam is deflected by a shock nearly parallel to the surface of the cloud and the pressure behind this induces a second shock which slowly propagates into the dense cloud causing an increase in its central density by a factor $\sim 1.5$, from 1850 $n_a$ before the impact to $\sim 2800 n_a$ at the quasi-steady regime (see below) which is attained after the impact (at $t/t_d > 4.0$). As expected from previous analytical study (CTR), due to the highly radiatively cooling regime (which is expected in protostellar outflows), the angle between the two shocks is very small and they are both effectively parallel to the cloud surface at the impact zone.

Due to the impact, the beam is initially deflected by an angle $\theta \simeq 40^\circ$ but this deflection angle tends to decrease with time as the beam partially penetrates the cloud and describes a C-shaped trajectory around the curved jet/cloud contact discontinuity. After $t/t_d = 4.5$, the bow shock leaves the computational domain and the deflected beam propagates at an
apparently quasi-steady state regime with nearly constant deflection angle $\theta \simeq 30^\circ$ and velocity field distribution. Later on, however, as the jet slowly excavates a way through the dense cloud this regime must have an end and the jet will continue its propagation without significant deflection (see below).

Weak internal knots develop along the deflected beam as indicated in Fig. 1 and also by the density and pressure profiles across the flow depicted in Fig. 2, for $t/t_d = 4$ and 6.5. In the first stages of the interaction, the velocity field along the deflected beam is somewhat complex with velocity fluctuations along the ejected parts of the beam which are correlated with the positions of the knots. At $t/t_d = 4$, it varies from $\sim 11.8 c_a$ near the region of impact, to $\sim 12.3 c_a$ at $x = 4 R_j$, $\sim 10.0 c_a$ at $x = 5 R_j$, and $\sim 10.5 c_a$ at $x = 10 R_j$. Later on, the velocity field tends to become more uniform and slightly decreases with distance from the impact region. At $t/t_d = 6.5$, it decreases from $\sim 11.8 c_a$ near the region of impact to $\sim 10.5 c_a$ in the middle and $\sim 10 c_a$ at the end of the outflow. This corresponds to an average velocity for the deflected beam $v_j' \simeq 10.8 c_a$, which is compatible with the expected value (see e.g., CTR)

$$v_j' \simeq v_j \cos \theta,$$

which gives $v_j' \simeq 10.4 c_a$ (for $v_j = 12 c_a$ and $\theta \simeq 30^\circ$).

Before the impact, the bow shock propagates downstream with a speed (GB93) $v_{bs} \simeq v_j/[1 + (\eta \alpha)^{-1/2}] \simeq 8$, and after the impact $v_{bs}' \simeq 5.5$, which roughly agrees with the predicted estimate $v_{bs}' \simeq v_j'/[1 + (\eta \alpha)^{-1/2}] \simeq 5$, for a measured $\alpha = (R_j/R_h)^2 \simeq 1/4$ from the simulation (where $R_h$ is the radius at the jet head which is initially equal to $R_j$ and increases by a factor about two after the impact, see Fig. 1). The impact reduces the jet collimation, as expected (e.g., CTR, Raga & Canto 1995), and the reflected beam has an initial opening angle $\psi \simeq 30^\circ$ which reduces to $\psi \simeq 20^\circ$, as indicated by the density contour maps of Fig. 1, after $t/t_d = 4$. 
We note that the deflected jet fades as it propagates downstream at a distance $\sim 10R_j$ and this fading can be testified by the density and pressure profiles across the flow depicted in Fig. 2, for $t/t_d = 6.5$. This fading is in part caused by a drastic spreading of the jet material in the other directions mainly due to the more frontal interaction that the beam experiences with the cloud in the x-z plane (see Fig. 3). For comparison, Figure 4 shows the result of a jet/cloud interaction for a system with the same initial conditions as those in Fig. 1 except that the cloud is positioned off-axis also in the x-z plane, i.e., it has central coordinates $(0, 1.2 R_j, 1.2 R_j)$ and is located in one of the quadrants of the y-z plane. In this case, the jet effectively impacts a smaller section of the cloud and the collision is therefore much weaker — since the density in the cloud decreases from the center to the edges according to Eq. (1), the effective density parameter $\beta$ is larger by almost an order of magnitude than that of Fig. 1 ($\beta \simeq 2 \times 10^{-1}$). As a consequence, the deflection angle of the beam is smaller (at the time depicted, $\theta \simeq 16^\circ$ against $\theta \simeq 30^\circ$ in Fig. 1). In Fig. 4, we also note that the interaction between the beam and the cloud is almost completed. The jet has already penetrated most of the cloud extension and is resuming its original direction of propagation. Consistently, the deflected jet of Fig. 4 has a propagation velocity $(v'_j \simeq 11.5c_a \simeq v_j \cos\theta)$ which is larger than that of Fig. 1, and is fading earlier as indicated by the density contour map (the jet density decreases to less than $n_a$ above $5R_j$).

We can estimate a lower limit for the survival time $t_c$ of the jet/cloud interaction and the complete depletion of the deflected beam by evaluating the time that the second shock takes to travel over the cloud diameter $d_c = 2R_c = fR_j$ (where $f > 0$ is a multiple factor of the jet radius). One-dimension momentum flux conservation argument and the resulting shock geometry for a radiatively cooling jet interacting with a cloud of constant density and a density parameter $\beta = (n_j/n_c)^{1/2} \ll 1$ yields a cloud shock speed $v_{cs} \simeq \beta v_j \sin\theta$ (see e.g.,
and \( t_c \gtrsim \frac{d_c}{v_{cs}} \) or

\[
\frac{t_c}{t_d} \gtrsim \frac{f}{M_a \beta \sin \theta}
\]

For the deflected jet of Fig. 1 this equation gives \( \frac{t_c}{t_d} \gtrsim 7.5 \) (for an average \( \theta = 34^\circ \) and \( f = 2 \)), so that after this time, we would expect the incident beam to have penetrated the cloud almost completely thus suffering no more deflection. This time is, however, just a lower limit because as the jet penetrates the cloud both the deflection angle and the density parameter \( \beta \) decrease (due to the compression of the cloud) thus increasing \( t_c \) in the equation above. For the jet in Fig. 4 we estimate \( \frac{t_c}{t_d} > 3 \).

Figure 5 depicts the mid-plane density contour and the velocity field distribution of five radiative cooling jets interacting with clouds with different initial values of jet/cloud density parameter \( \beta \). All the incident jets have the same initial conditions as in Fig. 1. The top jet is propagating into a homogeneous medium and thus suffers no deflection. The four other systems have \( \beta \approx 2 \times 10^{-1}, 7 \times 10^{-2}, 4 \times 10^{-2} \) (as in Fig. 1), and \( 3.5 \times 10^{-2} \) from top to bottom, respectively. As expected, the angle of deflection increases with the increase of the density of the cloud (smaller \( \beta \)) and the larger the angle the slower the propagation speed of the deflected beam. Likewise, the interaction time increases with decreasing \( \beta \) (Eq. 4) and the jet with \( \beta \approx 2 \times 10^{-1} \) (Fig. 5, second panel), for example, has already practically resumed its initial direction of propagation after partially destroying the cloud, while the jet with \( 3.5 \times 10^{-2} \) (bottom) is still interacting with the cloud. Equation (3) gives the following lower limit interaction times: \( \frac{t_c}{t_d} > 0, 2.5, 5, 7.5, \) and 8.5, respectively. (We note, however, that Eq. (3) is valid essentially for \( \beta \ll 1 \) so that the estimated values above for \( t_c \) for the systems with larger \( \beta \) are less reliable). Figure 6 shows the evolution of an interacting system with initial conditions similar to those of Figs. 1 and 5 but the cloud has now a radius twice as bigger \( (R_c = 2R_j) \) and an effective density parameter \( \beta \approx 6 \times 10^{-2} \) (which is comparable to that of the third jet of
Figure 5). The larger cross section of the obstacle causes the deflection angle of the beam to be larger and the interaction time much longer (Eq. 4 gives $t_c/t_d > 9.3$, for a cloud diameter $d_c = 4R_j$, or $f = 4$).

The compressing shock increases the central density of the cloud to a maximum factor $\simeq 1.4$ and the deflection angle of the beam varies from $\theta \simeq 45^\circ$ (at the initial impact at $t/t_d = 2$) to $\theta \simeq 40^\circ$ after $t/t_d = 3.5$ (against $\theta \simeq 25^\circ$ in the third jet of Fig. 5, and $\theta \simeq 35^\circ$ in the jet of Fig. 1 at the same evolution time). Consistent with these deflection angles (Eq. 3), the average velocity of the deflected beam varies from $v'_{j} \simeq 9$ to $7c_a$, and the bow shock velocity decreases from $\simeq 8c_a$ before the impact to $\simeq 5c_a$ after it. The opening angle of the deflected beam varies from $\psi \simeq 35^\circ$ to $\psi \simeq 25^\circ$, as indicated by the density contour maps of Fig. 6. The density contour maps also indicate the formation of some bright knots along the deflected beam and bow shock. Those knots have densities $n_k/n_a \simeq 5$ to 15 and were originally produced in the region of impact at the contact discontinuity and carried downstream by the deflected jet. At $t/t_d = 7$, the density in the deflected beam decreases from $n'_{j}/n_a \simeq 5$ near the impact to less than 1 above $\sim 5R_j$.

3.2. Jet/Cloud Off-Axis Interactions for Jets with Different $M_a$

Figure 7 depicts two interacting systems with different initial ambient Mach numbers, $M_a = 12$ (top) and 18 (bottom). Both jets have an initial density parameter $\beta \simeq 3.5 \times 10^{-2}$ and the other initial conditions are the same as in Figs. 1 and 5. (Note that the jet with $M_a = 12$ is the same jet in the bottom panel of Fig. 5.) The jet with larger $M_a$ interacts faster with the cloud (Eq. 4) and thus fades earlier too ($t_c/t_d > 6$ and 8.5, for the $M_a = 18$ and 12, respectively). At the time depicted in Fig. 7, the $M_a = 18$ jet is already starting resuming its original direction. Initially, both systems have similar deflection angles ($\theta \simeq 40^\circ$) but because of the larger interaction rate of the $M_a = 18$ jet, at the time depicted its angle has
become smaller ($\theta \simeq 35^\circ$ in the $M_a = 18$, against $\theta \simeq 40^\circ$ in the $M_a = 12$ jet). The density in the deflected beam decreases from $n'_j/n_a \simeq 8$ near the impact region, to less than unity above a distance $\sim 5R_j$ in the $M_a = 18$ jet, while in the $M_a = 12$ it decreases from $n'_j/n_a \simeq 11$ near the impact region, to $\sim 2.4$ at $\sim 5R_j$, and less than unity above $\sim 8R_j$.

Figure 8 shows an example of an even higher Mach number jet ($M_a = 24$) after it had impacted a cloud (in an off-axis collision) with a relatively large density parameter ($\beta \simeq 2 \times 10^{-1}$ which is comparable to that of the second jet in Fig. 5). (The counterpart of this jet propagating into an initial homogeneous environment can be found, e.g., in GBB96, and Cerqueira, de Gouveia Dal Pino & Herant 1997.) In the time depicted in the figure, the interaction has already finished and the jet has completely resumed its original propagation direction but the interaction left some interesting signatures in the system. We see that the remains of the cloud are still present at $x = 0$ and have been involved by the bow shock structure. Also, part of the dense shell that developed at the head of the beam from the cooling of the shocked jet material has been detached from the head by the collision and left behind in the cocoon causing a remarkable asymmetry in the jet head region.

### 3.3. Frontal Jet/Cloud Interactions

Figure 9 shows an example of a strong frontal impact of a jet with a dense cloud with a density parameter $\beta \simeq 7 \times 10^{-2}$. The initial conditions in this system are the same as in the third jet of Fig. 5 except for the location of the cloud which now has coordinates $(0, 0, 0)$. The frontal collision is obviously much stronger and the compression increases the density of the cloud by a factor $\sim 2.5$ (from $n_c/n_a \simeq 700$ before the impact, to $n_c/n_a \simeq 1800$ after it). The jet splits into two beams on either side of the cloud with equal deflection angle $\theta \simeq 45^\circ$ and a double bow shock structure (or double lobes) develops. By the time the bow shocks leave the computational domain ($t/t_d \simeq 6$) most of the cloud has been destroyed.
by the interaction and the double deflected beam has almost faded, although the jet has not yet completely resumed its original direction. The propagation velocity of the deflected beams varies from 7 to 10 $c_a$ along the flow, and the average density in the post-impact beam is $\sim 4 n_a$. Simulations involving weaker frontal interactions with less dense clouds have shown that the beam easily sweeps the cloud material to the working surface causing it to become more knotty and wider.

### 3.4. Adiabatic Jet/Cloud Interactions

Figure 10 shows the density in the mid-plane section and the velocity field distribution of an adiabatic jet which is interacting with a (adiabatic) cloud in an off-axis collision after it had propagated over a distance $\sim 30R_j$. The initial conditions are the same as in Figure 1. The interaction causes a compression in the interacting cloud of the same amount as that produced by the radiatively cooling jet (by a factor $\sim 1.5$) but the adiabatic jet penetrates less deeply into the cloud describing a more pronounced C-shaped trajectory around the contact discontinuity. The deflection angle is in turn larger ($\theta \simeq 40^\circ$ against $\theta \simeq 35^\circ$ in the radiatively cooling jet at $t/t_d =4$) and so the opening angle (as indicated by the density contour maps $\psi \simeq 35^\circ$ in the adiabatic jet and $\psi \simeq 16^\circ$ in the radiatively cooling counterpart in Fig. 1). This result is consistent with previous analytical and two-dimensional numerical studies of the interaction of adiabatic and radiatively cooling jets with plane-parallel and spherically stratified clouds (Canto & Raga 1996, Raga & Canto 1996). At the time depicted, the adiabatic jet is trying to resume its original direction causing the fading of the deflected beam (the density in the deflected beam decreases from $n_j'/n_a \simeq 9.5$ near the impact region to less than unity at a distance $\sim 4R_j$ in the adiabatic jet, while it decreases from $n_j'/n_a \simeq 11.5$ to 1 at a distance $\sim 10R_j$ in the cooling jet). The average velocity in the adiabatic and radiatively cooling deflected beams are of the same
order $v'^j \approx 11 c_a$.

4. Discussion and Conclusions

We have presented the results of fully three-dimensional simulations of overdense, radiatively cooling and adiabatic jets colliding with dense, compact ambient clouds. Frontal and off-axis collisions were examined. Evaluated for a set of parameters which are particularly appropriate to protostellar jets [with initial density ratios between the jet and the ambient medium $\eta \approx 3$, ambient Mach numbers $M_a \approx 12 - 24$, and jet/cloud density parameters $\beta = \left( \frac{n_j}{n_c} \right)^{1/2} \approx 3.5 \times 10^{-2} - 2 \times 10^{-1}$], our results indicate that important transient and also permanent effects may occur on the jet as a consequence of the interaction. Our main results can be summarized as follows.

1. As in previous analytical and two-dimensional numerical study (CTR, Raga & Canto 1995), we find that the primary effect of a radiatively cooling jet/cloud collision is to deflect the beam by a shock to a direction initially nearly parallel to the surface of the cloud at the impact region. A secondary shock, which is induced by the increased pressure behind the first, slowly propagates into the dense cloud causing an overall increase in its density.

2. The deflected beam initially describes a C-shaped trajectory around the curved jet/cloud contact discontinuity but the deflected 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. Due to the small size of the clouds [with radius $R_c \approx (1 - 2)R_j$], the lifetimes of the interactions deduced from the simulations are only $\sim$ few 10 to $\sim$ few 100 yr (for jets with $M_a = 24 - 12$) but they are longer than the predicted time from analytical modeling (Eq.3; see also Raga & Canto 95).
3. During the interaction, weak internal knots develop along the deflected beam. The velocity field initially has a complex structure with variations along the flow that later evolves to a more uniform distribution. At the region of impact the velocity is the order of the incident jet velocity, but the average velocity of the deflected beam is compatible with the predicted value $v'_j \simeq v_j \cos \theta$, where $\theta$ is the deflection angle, and $v_j$ is the velocity of the incident beam (e.g., CTR). The impact also increases the jet opening angle, as expected.

4. Jets in off-axis collisions with clouds with different density parameter $\beta$ result in different deflection angles and interacting times — the larger the density of the cloud (the smaller the $\beta$) the larger the angle and the longer the interaction time (Fig. 5). The increase in the radius of the cloud also makes the deflection angle and the interaction time larger, while the increase in the incident jet Mach number, $M_a$, naturally decreases the time of the interaction.

5. Frontal collisions with very dense clouds, although they are expected to be even rarer, may also produce peculiar transient features. They are naturally stronger and faster than off-axis interactions with similar initial conditions. Such interactions cause the splitting of the jet into two beams which produce a double bow shock structure on either side of the cloud. This is, however, a very transient feature and thus highly unlikely to be observed. Weaker frontal interactions, on the other hand, do not produce a jet splitting and most of the cloud material is simply swept to the working surface at the jet head.

6. Adiabatic jets interacting with clouds in off-axis collisions penetrate less deeply into the cloud and describe a more pronounced C-shaped trajectory around the contact discontinuity. The deflection angle is in turn larger than that in its radiatively cooling counterpart. This result is consistent with previous analytical and two-dimensional numerical studies involving jet interactions with plane-parallel and spherically stratified obstacles (Canto & Raga 1996, Raga & Canto 1996).
The basic features found above in the deflected beam, such as the decrease in the jet velocity and the increase in the opening angle with respect to the incident beam, have been detected in the HH 110 jet (Reipurth et al. 1996, Rodriguez et al. 1998) which is possibly the most convincing example, among the protostellar jets, of beam deflection by interaction with an ambient cloud. As stressed by those authors, no driving source has been detected at the apex of the HH 110 jet and it seems to be the deflected part of the fainter HH 270 jet. They have proposed that the deflection is caused by an interaction of the jet with a dense cloud core with $\beta \simeq 0.03 - 0.3$. Since this system seems to lie close to the plane of the sky we may directly compare its morphology with the results of the simulations. Although the measured deflected angle ($\sim 58^\circ$) is larger than those obtained in our simulations, the head – neck bright structure we see in the density contour maps of the off-axis simulations at the region of impact in strong interactions (see Figs. 1, 5, 6, and 7), is remarkably similar to the morphology of the HH 110 knot A located at the apex of the HH 110 in the region where the deflection of the HH 270 jet is believed to occur (see Fig. 6 of Reipurth et al. 1996). Besides, the HH 110 flow is observed to have a well collimated chain of knots near the apex and then to widen in a cone of large opening angle ($\psi \simeq 12^\circ$), until it fades in a final curve (Reipurth et al. 1996). All those morphological characteristics are clearly detected in our off-axis simulations, and the wide range of proper motions measured for the knots in HH 110 is compatible with the complex velocity structure found in the deflected beams. Furthermore, the estimated average velocity of HH 110 is consistent with the $v_j' \simeq v_j \cos \theta$ relation (Reipurth et al. 1996). All these similarities strongly support the proposed jet/cloud interaction interpretation for the HH 110/HH 270 system. The fact that the deflection angles derived from the simulations are smaller and the opening angles are larger than those observed in the HH 270/HH 110 system [even for the simulations involving an incident jet with $v_j \simeq 300 \text{ km s}^{-1}$ (or $M_a = 18$) which is the order of that inferred from observations] and the fact that the jet/cloud interaction is probably still taking place (thus
requiring an interacting time $\simeq$ the dynamical time of the deflected jet), indicate that the interacting cloud in that system must have a radius $R_c \gg R_j$, as suggested by Reipurth et al. (1996), and a density parameter $\beta \lesssim 0.1$, as indicated by the simulations.

Applied to the general context of the protostellar jets, the interactions examined here are essentially transient processes and thus the probability of them being observed must be very small, since the typical dynamical lifetimes of the observed outflows ($\tau \gtrsim 10^4$ yr; e.g., Bally & Devine 1997) are much larger than the inferred survival times of the jet/cloud interactions. Nonetheless these interactions may leave a variety of interesting more permanent features imprinted in the remaining outflow. For example, we have found that after a weak interaction of only few decades with a compact cloud (with density parameter $\beta \simeq 0.2$) the $M_a = 24$ jet has retained in its working surface the remains of the cloud, and some fragments of the dense shell have been detached from the head during the collision producing remarkable asymmetries in the beam (Fig. 8). Weak interactions are also able to produce some wiggling in the deflected beam (Figs. 5 and 8) but this feature will last not much longer than the interaction. The production of jet wiggling by the interaction with a plane-parallel stratified environment was also reported in previous numerical studies (GBB96; GB96).

The simulations also indicate that before a deflected beam fades it may have time enough to produce and deposit some knots into the working surface at the jet head (see, e.g., Fig. 6) which may contribute to enrich and enlarge the knotty pattern behind the bow shock. Since this clumpy structure resembles the knotty pattern commonly observed in HH jets, this result suggests that transient jet/cloud interactions may also play an important role in the formation of these HH structures.

Finally, we should also note that 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 over a transverse extension which will depend on the deflection angle of each interaction (Figs. 6 and 7). This process may be therefore, a powerful tool for momentum transfer and turbulent mixing with the ambient medium—a process that may help to feed the slower and wider molecular outflows often associated with protostellar jets (see e.g., Raga et al. 1993, Chernin et al. 1994, Cabrit et al. 1997).

This work was partially supported by the Brazilian agencies FAPESP and CNPq. The author is indebted to the referee Paul Wiita for his fruitful comments. The author also would like to acknowledge the kind hospitality of the Star Formation Group of the Astronomy Department of the University of California at Berkeley where most of this work was done and also relevant and clarifying discussions with Frank Shu and Bo Reipurth. Technical support from A.H. Cerqueira is also acknowledged.
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Table 1: The models and their initial physical parameters.

| Figures | $M_a$ | $M_j$ | $\eta$ | $\beta$ | $R_c/R_j$ | Collision | Cooling |
|---------|-------|-------|--------|---------|-----------|-----------|---------|
| 1, 2, 3, 4, 5 | 12 | 20.8 | 3 | $4 \times 10^{-2}$ | 1 | off-axis | yes |
| 5     | 12 | 20.8 | 3 | $\sqrt{\infty}$ | 1 | – | yes |
| 5     | 12 | 20.8 | 3 | $2 \times 10^{-1}$ | 1 | off-axis | yes |
| 5     | 12 | 20.8 | 3 | $7 \times 10^{-2}$ | 1 | off-axis | yes |
| 5, 7  | 12 | 20.8 | 3 | $3.5 \times 10^{-2}$ | 1 | off-axis | yes |
| 6     | 12 | 20.8 | 3 | $6 \times 10^{-2}$ | 2 | off-axis | yes |
| 7     | 18 | 31.3 | 3 | $3.5 \times 10^{-2}$ | 1 | off-axis | yes |
| 8     | 24 | 41.7 | 3 | $2 \times 10^{-1}$ | 1 | off-axis | yes |
| 9     | 12 | 20.8 | 3 | $7 \times 10^{-2}$ | 1 | frontal | yes |
| 10    | 12 | 20.8 | 3 | $4 \times 10^{-2}$ | 1 | off-axis | no |
**FIGURE CAPTIONS**

**Figure 1:** Mid-plane density contour (left) and velocity field distribution (right) evolution of a radiatively cooling jet interacting with a cloud with radius $R_c = R_j$, central coordinates $(0, 1.2 R_j, 0)$, and a Gaussian density (and pressure) profile of width $\sigma = 0.75 R_j$. The initial conditions for the jet are: $\eta = n_j/n_a = 3$, $n_a = 200 \text{ cm}^{-3}$, $M_a = 12$, $v_j \simeq 200 \text{ km s}^{-1}$, radiatively cooling length parameter behind the bow shock $q_{bs} \simeq 0.5$ and behind the jet shock $q_{js} \simeq \eta^{-3} q_{bs} \simeq 2 \times 10^{-2}$ (GB93). The square root of the density ratio between the jet and the center of the cloud is $\beta = (n_j/n_c)^{1/2} \simeq 4 \times 10^{-2}$. The times depicted are: $t/t_d = 2.0, 3.0, 4.0, 5.0$ and $6.5$ ($t_d = R_j/c_a \simeq 38$ years). The distances are in units of $R_j = 2 \times 10^{15}$ cm and the jet was injected at $x \simeq -16 R_j$. The density lines are separated by a factor of 1.3 in the second and third panels, and 1.2 in the rest. The density scale covers the range, from top to bottom: $\sim (4 \times 10^{-1} - 2.8 \times 10^3) n_a$, $\sim (10^{-1} - 5.0 \times 10^3) n_a$, $\sim (10^{-1} - 3.6 \times 10^3) n_a$, $\sim (4 \times 10^{-1} - 2.9 \times 10^3) n_a$, and $\sim (4 \times 10^{-1} - 2.9 \times 10^3) n_a$.

**Figure 2:** Density (solid line) and pressure (dashed line) profiles across the flow of Fig. 1 at different positions along the flow at $t/t_d \simeq 4.0$ (top) and 6.5 (bottom). The peaks on the left side of the jet axis trace the propagation direction of the deflected beam. The density and pressure scales can be calibrated using the marker in the top region of the plot (the marker for the density corresponds to $\sim 1.7 n_a$, and the marker for the pressure corresponds to $\sim 3.5 p_a$, where $p_a \simeq 9.3 \times 10^{-10} \text{ dyn cm}^{-2}$). The density and pressure are very high at the impact region (at $x= 0$) and have been clipped to highlight the low level features in the deflected beam.

**Figure 3:** The jet/cloud system of Fig. 1 seen in the x-z plane at $t/t_d = 6.5$. Due to the position of the cloud, which has central coordinates $(0, 1.2 R_j, 0)$, the jet/cloud collision seen from this plane looks *frontal*.

**Figure 4:** Mid-plane density contour (top) and velocity field distribution (bottom) of a
radiatively cooling jet interacting with a cloud with radius $R_c = R_j$ and central coordinates $(0, 1.2 R_j, 1.2 R_j)$ at a time $t/t_d = 6.5$. The other initial conditions are the same as in Fig. 1. The collision is this case is off-axis in both planes x-y and x-z. In the contour plot, the density lines are separated by a factor 1.2 and the density scale covers the range $\sim (4 \times 10^{-2} - 2.9 \times 10^2) n_a$.

**Figure 5:** Mid-plane density contour (left) and velocity field distribution (right) of five radiatively cooling jets interacting with clouds with different initial density parameter $\beta$ after they have propagated over a distance $\approx 30 R_j$ (corresponding to $t/t_d = 3.5$ for the first panel and $t/t_d = 4$ for the rest). From top to bottom: $\beta \approx \sqrt{\infty}$, $2 \times 10^{-1}$, $7 \times 10^{-2}$, $4 \times 10^{-2}$, and $3.5 \times 10^{-2}$. The other initial conditions are the same as in Fig. 1. The deflection angle in each case, from top to bottom, is: $\theta \approx 0^o$, $15^o$, $25^o$, $35^o$, and $40^o$, respectively. The density scale in the contour maps covers the range, from top to bottom: $\sim (2 \times 10^{-1} - 8.7 \times 10^1) n_a$, $\sim (4 \times 10^{-1} - 7.4 \times 10^1) n_a$, $\sim (5 \times 10^{-1} - 9.5 \times 10^2) n_a$, $\sim (10^{-1} - 3.6 \times 10^3) n_a$, and $\sim (7 \times 10^{-1} - 5.3 \times 10^2) n_a$.

**Figure 6:** Mid-plane density contour (left) and velocity field distribution (right) evolution of a radiatively cooling jet interacting with a cloud with radius $R_c = 2 R_j$ and central coordinates $(0, 1.2 R_j, 0)$. The density parameter is $\beta \approx 6 \times 10^{-2}$ (which is comparable to that of the third jet of Figure 5). The other initial conditions are the same as in Figs. 1 and 5. The times depicted are: $t/t_d = 2.5$, 4.5, 5.5 and 7.0. The density scale in the contour maps covers the range, from top to bottom: $\sim (3 \times 10^{-1} - 2.2 \times 10^3) n_a$, $\sim (2 \times 10^{-1} - 1.8 \times 10^3) n_a$, $\sim (2 \times 10^{-1} - 1.6 \times 10^3) n_a$, and $\sim (2 \times 10^{-1} - 1.4 \times 10^3) n_a$.

**Figure 7:** Mid-plane density contour and velocity field distribution of two radiatively cooling jet/cloud systems with different initial jet Mach numbers $M_a = 12$ (top) and 18 (bottom), after they have propagated over a distance $\approx 30 R_j$ at $t/t_d = 4$. Both jets have an initial density parameter $\beta \approx 3.5 \times 10^{-2}$ and the other initial conditions are the same as
in Fig.1. (Note that the jet with $M_a = 12$ is the same of the bottom panel of Fig. 5.) The density scale in the contour maps covers the range: $\sim (7 \times 10^{-1} - 5.3 \times 10^3) n_a$ (top), and $\sim (8 \times 10^{-1} - 5.8 \times 10^3) n_a$ (bottom).

**Figure 8:** Mid-plane density contour (top) and velocity field distribution (bottom) of an $M_a = 24$ radiatively cooling at $t/t_d = 1.7$ after interacting with a cloud with radius $R_c = R_j$ and central coordinates $(0, 1.2 R_j, 0)$. The square root of the jet to central cloud density ratio is $\beta \approx 2 \times 10^{-1}$ and the initial conditions for the jet are: $\eta = n_j/n_a = 3$, $v_j \approx 400$ km s$^{-1}$, $q_{bs} \approx 8$, and $q_{js} \approx 0.3$. The density lines are separated by a factor of 1.2 and the density scale covers the range: $\sim (2 \times 10^{-1} - 2.4 \times 10^2) n_a$.

**Figure 9:** Frontal impact of a jet with a dense cloud of central coordinates $(0, 0, 0)$ and a density parameter $\beta \approx 7 \times 10^{-2}$ (the same as in the third jet of Fig. 5). The other initial conditions are the same as in Fig. 1. The times depicted are: $t/t_d = 3.5$, and 6.0. The density lines are separated by a factor of 1.2 and the density scale covers the range: $\sim (2 \times 10^{-1} - 1.6 \times 10^3) n_a$ (top), and $\sim (2 \times 10^{-1} - 1.5 \times 10^3) n_a$ (bottom).

**Figure 10:** Mid-plane density and velocity field distribution of an adiabatic jet interacting with a cloud in an off-axis collision after it had propagated over a distance $\sim 30 R_j$ at $t/t_d = 4$. The initial conditions are the same as in Figure 1. The density scale in the contour map covers the range $\sim (4 \times 10^{-1} - 2.5 \times 10^3) n_a$. 

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