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COLLISIONS OF OUTFLOWS WITH INTERSTELLAR CLOUDS

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RESUMEN

Los objetos HH tienen una posibilidad finita de chocar con obstáculos densos (por ejemplo, núcleos moleculares compactos) que se encuentren a lo largo de la trayectoria del flujo. Observaciones recientes que indican que HH 110 puede ser un chorro que sufre tal colisión, nos han motivado a desarrollar la teoría de colisiones radiativas entre chorros y nubes densas. El presente artículo es un resumen de nuestro trabajo, que ha estado dirigido a explorar tanto la evolución inicial como la configuración estacionaria final de las colisiones de chorros con nubes densas. Encontramos que las predicciones de nuestros modelos analíticos y numéricos coinciden sorprendentemente bien con las observaciones de HH 110.

ABSTRACT

HH jets have a finite chance of hitting dense obstacles (e.g., a molecular cloud core) present along their direction of propagation. Recent observations that indicate that HH 110 might correspond to a jet going through such a collision have motivated us to develop the theory of radiative jet/cloud collisions. This paper reviews our recent work on this subject, which has been concerned with studying both the initial evolution and the final, steady configuration of jet/cloud collisions. We find that the predictions from our analytic and numerical models agree surprisingly well with the observations of HH 110.

Key words: **ISM: JETS AND OUTFLOWS — STARS: FORMATION**

1. INTRODUCTION

As other large cities, Mexico City has a quite extreme number density of cars with a high flow velocity along the city streets. This situation provides an ideal laboratory for studying collisions of cars with both soft (pedestrian) or hard obstacles (other cars, trucks, lamposts, etc.). A similar situation is found in regions of star formation, where HH jets have a finite probability of hitting soft (e.g., density perturbations in the environment) or hard obstacles (e.g., molecular cloud cores).

The paper of Henney (1995) describes the effects of environmental density perturbations on the head of an overdense HH jet; i.e., the case of the collision of a jet with "soft obstacles". In the following, we will describe the interaction of an HH jet with a dense obstacle, which could be a molecular cloud core present along the path of the jet. Such an interaction clearly leads to important effects on the dynamical properties of the jet.

We have divided the discussion of the jet/cloud core collision into two parts. In the first, we discuss the initial evolution of the flow that is generated when the head of the jet first collides with the surface of the dense cloud (following the work of Raga & Cantó 1995a). In the second, we discuss the final, steady configuration attained when the jet has bored through the stratified obstacle (following the work of Cantó & Raga 1995 and Raga & Cantó 1995b).

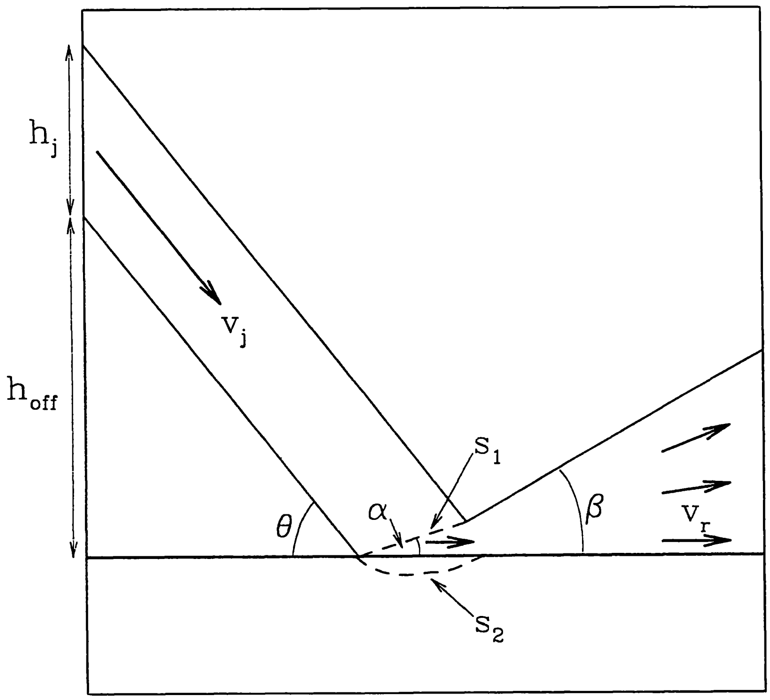

Fig. 1. Schematic diagram showing the interaction of a jet of width h_j hitting a cloud of radius $r_c \gg h_j$.

2. THE INITIAL EVOLUTION OF A JET/CLOUD COLLISION

When the head of a jet encounters a dense cloud (i.e., with $\rho_c \gg \rho_j$, where ρ_c and ρ_j are the cloud and jet densities, respectively) the beam of the jet is deflected so that it becomes roughly parallel to the surface of the cloud. This deflection takes place through a shock $S1$ which forms an angle α with the surface of the cloud (see Figure 1). Cantó, Tenorio-Tagle, & Różyczka (1988) have shown that for the radiative case this angle has a value $\alpha \ll 1$, so that the shock velocity of the $S1$ shock is given by

$$v_1 \approx v_j \sin\theta \,, \tag{1}$$

where v_j is the jet velocity and θ is the angle between the incident jet beam and the surface of the cloud (see Figure 1). The jet/cloud collision also drives a second shock $S2$ into the cloud (see Figure 1), with a shock velocity

$$v_2 \approx \sqrt{\frac{\rho_j}{\rho_c}}\, v_j \sin\theta \,. \tag{2}$$

Also, for the case of a highly radiative interaction it is possible to show that the velocity of the deflected jet beam after the jet/cloud interaction is given by

$$v_r \approx v_j \cos\theta \,, \tag{3}$$

and that the opening angle β (see Figure 1) of the deflected beam is given by

$$\sin\beta \approx \frac{2}{(\gamma - 1)\, M_{eq} \cos\theta} \,, \tag{4}$$

where M_{eq} is the Mach number of the incident jet beam with respect to the sound speed at the equilibrium temperature reached after the radiative $S1$ shock.

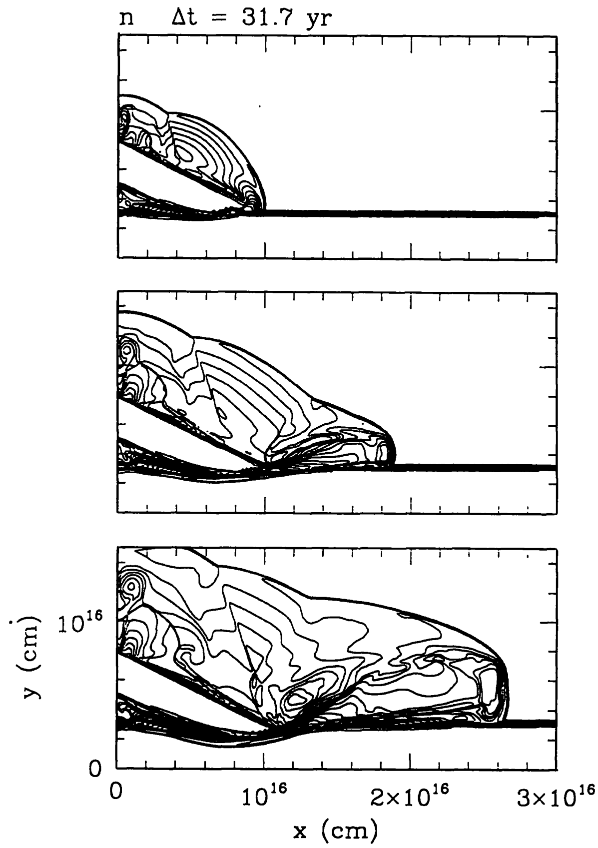

Fig. 2. Density time-sequence ($\sqrt{2}$ contours) showing a radiative slab jet hitting a dense, plane cloud.

Figure 2 shows a time-sequence of a radiative slab jet simulation carried out with the adaptive grid Coral code (Raga 1994). In this simulation, a jet with $v_j = 100$ km s^{-1} and $n_j = 5$ cm^{-3} impinges on a cloud of $n_c = 500$ cm^{-3} at an incidence angle $\theta = 25°$. The formation of a deflected jet beam is clearly seen.

This jet deflection effect, however, is only a transitory phenomenon, because at later times the deflected jet beam is choked off and the incident jet directly penetrates into the dense cloud. This pinching off effect is seen in Figure 3, which shows a later time in the evolution of our slab jet simulation.

It is possible to estimate the time t_c at which the deflected beam is choked off as

$$t_c \sim \sqrt{\frac{\rho_c}{\rho_j}}\frac{h_j}{v_j \sin\theta}, \tag{5}$$

which agrees to within a factor of ~ 2 with the results obtained from numerical simulations.

3. THE FINAL, STEADY CONFIGURATION

For times $t \gg t_c$ the jet will have bored a hole through the cloud and will achieve a final, steady configuration. In this final configuration the locus of the jet beam is determined by Bernoulli's theorem :

$$\frac{1}{2}v^2 - \frac{1}{2}{v_0}^2 = -\int_{P_0}^{P}\frac{dP}{\rho}, \tag{6}$$

where v_0 and P_0 are the velocity and pressure (respectively) of the jet at the point where the jet penetrates the cloud.

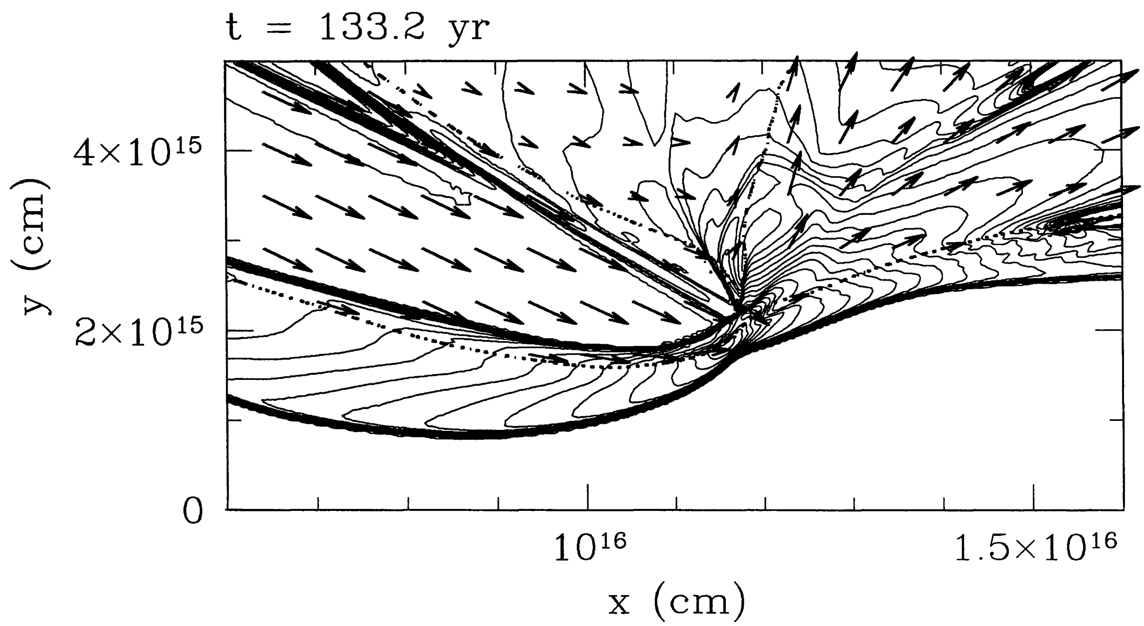

Fig. 3. Pressure stratification ($\sqrt{2}$ contours) of the jet/cloud collision region obtained after a time-integration of 133.2 years. The arrows show the flow velocity field and the dashed lines represent the jet/environment contact discontinuities.

The integral $\int dP/\rho$ can be computed analytically if one assumes that :

a. the jet beam is in local pressure balance with the surrounding environment, and

b. the jet is either isentropic or isothermal.

Once this integral is carried out, it is possible to use equation (6) to determine the locus of the jet beam as it travels through the cloud.

We have found analytic expressions for both adiabatic and isothermal jets traveling through a cloud with a plane, exponential pressure stratification (Cantó & Raga 1995). We have also computed steady, radiative slab jet simulations which show that an HH jet behaves approximately isothermally while it enters the stratified cloud (as the adiabatic compression heating is balanced by the radiative energy loss), and approximately adiabatically when it starts leaving the high pressure, inner regions of the cloud (as the adiabatic expansion cooling is not balanced by any heating term).

Figure 4 shows a comparison between a simulation of a radiative jet penetrating an exponential pressure stratification and a solution of Bernoulli's theorem (equation (6)) in which we assume that the jet behaves isothermally while it travels into the cloud (i.e., into regions of increasing pressure) and adiabatically as it travels down the pressure gradient. It is clear that the analytic solution of equation (6) quite accurately describes the locus of the jet beam obtained from the numerical simulation.

It is interesting to note that the jet is deflected on passage through the stratified environment, but only after going through many pressure scale heights. This result directly implies that only very slight jet deflections will be obtained for the case of a collision of a jet with a molecular cloud core, that has a pressure stratification similar to a singular, isothermal sphere ($P \propto r^{-2}$). In such a stratification, the pressure scale height is $H = r/2$, so that the jet will travel through many pressure scale heights (the necessary condition for obtaining an appreciable deflection of the jet beam) only in an almost head on collision with the cloud core.

This effect can be seen in Figure 5 in which we show the locus of the jet beam obtained from Bernoulli's theorem for collisions with different impact parameters. We see that even for an impact parameter as low as 0.05 times the outer radius of the cloud core, the locus of the jet beam deviates only slightly from a straight line.

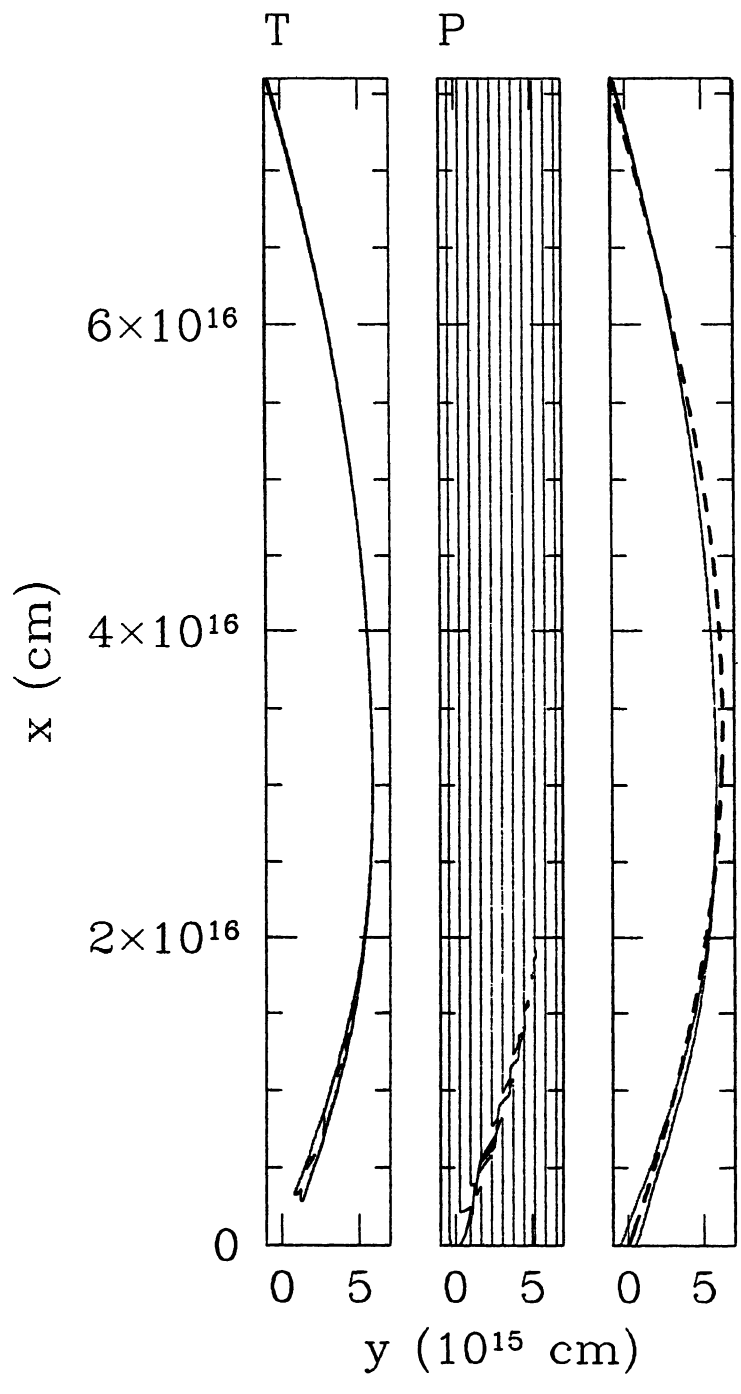

Fig. 4. Temperature and pressure stratification (left and center, $\sqrt{2}$ contours) resulting from a steady, radiative simulation of a slab jet traveling at an initial angle of 20° into a plane-parallel, exponential pressure distribution with a scale height $H = 2 \times 10^{15}$ cm. The jet has an initial diameter $D = 10^{15}$ cm, velocity $v_0 = 70$ km s^{-1} and temperature $T_0 = 10^4$ K . The graph on the right shows the edges of the jet beam (solid lines) computed numerically, and the locus of the jet beam (dashed line) obtained from Bernoulli's theorem.

The conclusion that can be reached from these results is that a jet/cloud core collision will initially lead to a deflection of the jet beam at the surface of the cloud. After a time $t_c \sim$ 100–1000 years (see equation (5)) the deflected jet beam will be pinched off and the jet will start to bore almost straight into the cloud, with only an almost imperceptible bending of the jet beam. The timescale for the existence of a deflected jet beam could be lengthened quite considerably if the direction of the incident jet beam were not completely steady, as the point of impact would then move across the surface of the cloud, therefore spreading the effect of the impact of the jet over a larger region of the cloud.

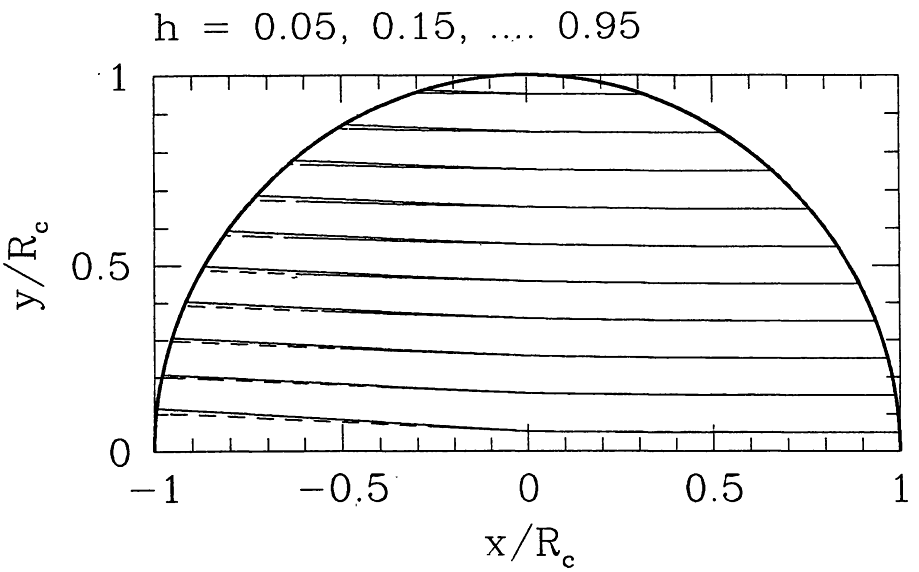

Fig. 5. The locus of the jet beam obtained from an isothermal entry/adiabatic exit numerical solution of Bernoulli's theorem for the case of a jet encountering a cloud core with a singular, isothermal sphere pressure stratification. The circle corresponds to the outer surface of the cloud core (of radius R_c) and the solid lines indicate the loci of the jet beam for jet/cloud collisions with different impact parameters h . The values of h of the trajectories shown in the graph are $h = 0.05, 0.15, 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, 0.85$ and 0.95, in units of the outer radius R_c of the cloud core. The dashed lines represent the same trajectories, but calculated with an approximate analytic solution of Bernoulli's theorem (Raga & Cantó 1995b).

4. OBSERVATIONS OF HH 110

HH 110 (Reipurth & Olberg 1991) is possibly the best candidate for a HH jet that is being deflected through a collision with a molecular cloud core. No source has been detected on the axis of this outflow, and a particularly high extinction region of the L1617 cloud lies directly to the North of this object. The HH 270 outflow (which apparently is associated with the source IRAS 05489+0256) is located NE of HH 110 (Reipurth & Cernicharo 1995; Reipurth, Raga, & Heathcote 1995). These two HH objects can be interpreted in terms of an incident jet (HH 270) that collides with a high density obstacle, producing a deflected jet beam (HH 110).

The proper motions determined by Reipurth et al. (1995) are consistent with this scenario, as shown in the schematic diagram of Figure 6. As all of the radial velocities measured for this system are much lower than the proper motions (in other words, the system has to be lying close to the plane of the sky), we would expect that the apparent deflection angle (of $\approx 58°$, see Figure 6) and the proper motions of the incident and deflected jet beams should satisfy equation (3). In effect, using the measured proper motions and equation (3), one obtains a deflection angle $\theta \approx 62°$, which agrees with the projected deflection angle measured in the images of HH 270/110 (see Figure 6) to an almost embarrassing degree of accuracy.

Another interesting observation of HH 110 has been recently reported by Davis, Mundt, & Eislöffel (1995), who detected H_2 $1-0$ s(1) emission. In their infrared image they see an elongated structure that approximately follows the west edge of the Hα emission of HH 110. This effect is illustrated by the schematic diagram of

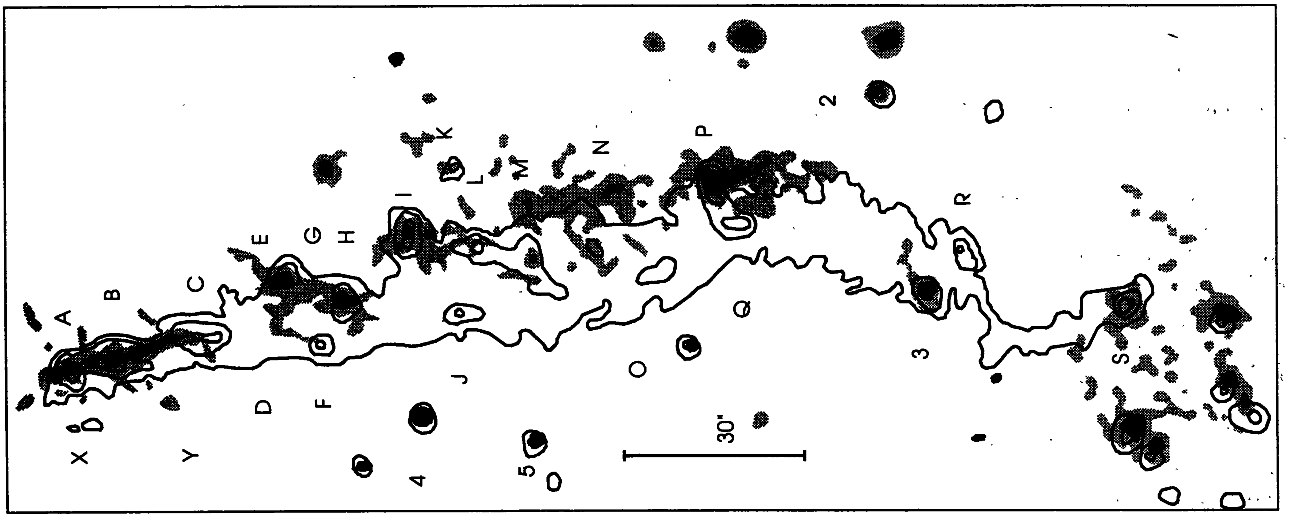

Fig. 6. Schematic diagram showing the general morphology of the [S II] λ6717+31 emission of HH 110 and HH 270. Also shown are the approximate position of the *IRAS* source and the average proper motions measured for HH 270 and HH 110. The axes of these two outflows intersect at an angle of 58° with respect to each other. The information for constructing this schematic diagram has been taken from Reipurth et al. (1995).

Figure 7, which shows a superposition of the H_2 image of Davis et al. (1995) and the Hα image of Reipurth & Olberg (1991). This H_2/Hα morphology difference is again consistent with a scenario in which HH 110 is formed by a deflection of HH 270 with a dense, molecular obstacle. In this scenario it would be expected that material from the molecular clump would be ablated in the jet/clump interaction region and dragged along the west side of HH 110. We plan to do a detailed calculation of this ablation process in the near future, extending the work on plane, molecular mixing layers of Taylor & Raga (1995).

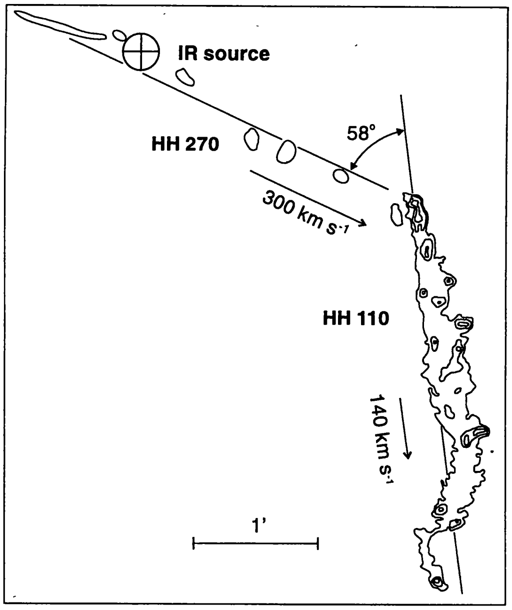

Fig. 7. Schematic diagram showing the morphology of the H_2 1 − 0 s(1) emission (from Davis et al. 1995) and the Hα emission (from Reipurth & Olberg 1991) of HH 110. It is clear that the H_2 emission approximately follows the west edge of the atomic hydrogen emission.

5. SUMMARY

We have presented a discussion of the collision of an HH jet with a dense obstacle (which could be a molecular cloud core) present along the path of the jet. Initially the jet is deflected on contact with the surface of the dense obstacle, forming a somewhat slower, less well-collimated deflected jet beam. At later times, the jet starts to drill a hole and eventually goes directly through the dense obstacle.

If the obstacle is stratified (e.g., if it is a singular, isothermal sphere) one would expect the path of the jet through the obstacle to be curved. However, we find that this curvature is almost imperceptible (particularly for the case of a radiative flow) except for jet/cloud collisions with very low impact parameters (i.e., almost head-on collisions). Because of this, if one observes a jet that is going through a strong deflection, this deflection has to correspond to the early stages of the jet/cloud collision, because at later stages the jet will be going almost straight through the obstacle. The duration of the jet deflection effect would be $\sim$ 100–1000 years for typical HH jet/cloud core parameters, but this can be lengthened appreciably if the incident jet beam does not have a completely steady direction of motion.

Finally, we have discussed recent observations of HH 270/110 which show a morphology, proper motions (Reipurth et al. 1995) and H_2 emission (Davis et al. 1995) which are surprisingly consistent with the expectations from our jet deflection models. It remains to be seen whether or not other "traffic accidents" such as this one are observed in the congested roads of star formation regions in which HH jets daily risk their lives.

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