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MODELS OF HH OBJECTS AND MOLECULAR OUTFLOWS

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RESUMEN

Se observa que las estrellas jóvenes, desde sus primeras etapas de evolución, producen flujos colimados de alta velocidad. Estos flujos son observados ópticamente como objetos Herbig-Haro (HH), y en ondas de radio como flujos moleculares. En este artículo se presentan modelos que tratan simultáneamente de explicar las características morfológicas y espectrales tanto de los objetos HH como de los flujos moleculares. Se discuten modelos de la interacción lateral entre el cuerpo del chorro y el medio ambiente, modelos de los efectos de una variabilidad temporal de la fuente, y modelos de la interacción de la cabeza de un chorro con el medio ambiente circundante. Finalmente, se discute la fuerte interacción que ocurre en una colisión de un chorro con una nube molecular compacta.

ABSTRACT

It is observed that from very early stages in their evolution, young stars produce high velocity, collimated outflows. These outflows are seen optically as Herbig-Haro (HH) objects and as molecular outflows at radio wavelengths. This paper discusses models which simultaneously attempt to explain the observed morphological and spectral characteristics of both HH objects and molecular outflows. Models of the lateral jet beam/environment interaction, models of the effects of a time-variability of the source, and models of the interaction of the head of a jet with the surrounding environment are discussed. Finally, the strong interaction that results from the collision of a jet with a molecular cloud core is described.

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

1. INTRODUCTION

1.1. HH Flows and Molecular Outflows

As discussed extensively in other papers in these Proceedings (e. g., Reipurth & Cernicharo 1995, Rodríguez 1995, Curiel 1995, Anglada 1995, Elitzur 1995, Lada & Fich 1995, Dyson et al. 1995, Giovanardi & Lizano 1995, Strom 1995, and Torrelles, Gómez, & Anglada 1995), there are a wide range of observations in different wavelength ranges indicating the presence of collimated outflows associated with young stellar objects. These outflows have velocities ranging from $\sim$ 10-30 km s^{-1}(which are typical of CO outflows) to $\sim$ 100-400 km s^{-1}(observed in the faster HH objects).

Many sources are associated with both a fast, very narrow HH flow and a slower, broader molecular outflow. It is somewhat tempting to try to interpret the quite different velocities and length-to-width ratios of HH flows and molecular outflows as evidence for the existence of two winds. For example, a fast wind from either the star or the central parts of an accretion disk could give rise to the HH flow, and a slower wind ejected from the outer parts of a disk could give rise to the molecular outflow. Furthermore, observations of the circumstellar

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region of some T Tauri stars can be interpreted as evidence for the existence of such a two-wind structure (see Solf & Böhm 1993, Hirth 1994, and the review of Reipurth & Cernicharo 1995 in these Proceedings).

However, the present review will stress a different point of view, in which the observations of both HH jets and molecular outflows are modeled as the result of a single, collimated flow. This "unified scenario" actually was the first suggestion made after the discovery of CO outflows, when it was speculated that the CO might be associated with environmental molecular material which is being "pushed" by an HH flow (see, e. g., Snell et al. 1985). The models discussed below are a continuation of this scenario, with of course a considerably larger degree of sophistication (some might even say obscurity) than the suggestions of 20 years ago.

In this unified scenario, the properties of the (optically detected) HH flows and the molecular outflows are intricately intertwined. Clearly, the HH flow/environment interaction of a well aligned, jet-like HH flow will be quite different from the one of an HH flow consisting of a number of independent "interstellar bullets". Because of this, in the following we will not attempt to separate the discussion of the properties of the HH flows from the molecular outflows.

The HH flows themselves show a wide range of properties, ranging from the more "well-behaved" HH jets (which show chains of well aligned knots) to very chaotic looking objects which appear to show a number of more or less independent "interstellar bullets" travelling away from the source in different directions. This difference in morphologies probably indicates an intrinsic difference in the way different HH flows are ejected from the source.

1.2. The Ejection Mechanism

The problem of the ejection of HH flows from the source will not be discussed in this review (this topic is discussed in the papers of Königl 1995 and Najita 1995 in these Proceedings). There is a quite wide range of hydrodynamic (Cantó 1983) and MHD (Pudritz 1988) models for the production of a continuous, jet-like flow, which of course can directly be associated with the observed HH jets.

However, it has proven to be much more difficult to model the production of the more chaotic, clumpy outflows. The "interstellar bullet" model of Norman & Silk (1979) hypothesized that high density clumps might be accelerated by the interaction with a fast wind from the central source, and that these clumps would then travel at high velocities into the surrounding interstellar medium. However, this scenario has fallen out of favour because numerical simulations (e. g., Nittman et al. 1982) appear to show that wind/clump interactions have the effect of disrupting the clump into small fragments, rather than accelerating the clump as a coherent entity.

This lack of a more or less realistic model for producing high velocity "bullets" appears to be one of the main problems in our understanding of the production of HH flows, as many of the HH objects clearly do not look like more or less continuous, jet-like flows. A possibility for getting around this problem is to eject a continuous, jet-like flow which then breaks into a number of clumps. In this way, one avoids the clump acceleration problem by producing the clumps out of an already fast moving outflow.

In this review, we will take this point of view, and assume that all HH flows are produced by the ejection of a high-velocity, collimated jet. We will then describe the conditions under which the jet breaks up into a number of independent "bullets".

1.3. Overview of the Paper

This paper first reviews the classical problem of a jet ejected from a source with time-independent properties (that is, the outflow is assumed to be "turned on" at a time $t = 0$, and to have a constant ejection for $t > 0$). The properties of such a jet are reviewed in section 2, which includes discussions on steady crossing shocks, turbulent mixing layers and simulations of the working surface.

In section 3, we remove the assumption of a time-independent ejection, and discuss the effects of a time variability in the magnitude and/or direction of the ejection velocity. The effects of such variabilities on the structure of the jet and on the interaction with the surrounding environment are described.

Finally, in section 4, we discuss the results of numerical simulations of a collision between a jet and a molecular cloud core. This has direct applications to the observations of HH 110 described by Reipurth & Cernicharo (1995) in these Proceedings.

2. JETS FROM STEADY SOURCES

2.1. General Considerations

Most of the available models of astrophysical jets have been calculated for a scenario in which a source producing an already collimated jet is instantaneously "turned on" at $t = 0$, and the conditions of the jet beam at the injection point are assumed to be time-independent for $t > 0$. This is of course a somewhat artificial scenario, since clearly there is no reason to suspect that such a sudden "turning on" actually occurs. Also, the condition of a completely steady injection condition (for $t > 0$) while reasonable for laboratory jets (which are produced with a rigid de Laval nozzle) is probably unrealistic in astrophysical jets (for which rigid nozzles clearly are not present !).

However, the problem of a jet from a steady source is important in that while having a lower degree of complexity it does show the main features of jet flows. These features are discussed in sections 2.2-2.4 .

2.2. Steady Crossing Shocks

In laboratory jet experiments it is found that after a timescale $\tau_{steady} \sim M_j r_j / v_j$ (where M_j, r_j and v_j are the initial Mach number, radius and velocity of the jet) a structure of steady "crossing shocks" begins to form in the region close to the source. These crossing shocks (see Figure 1) are the mechanism by which an initially under- or over-pressured jet beam tries to adjust its pressure to the environmental pressure, and their formation has been studied in detail in the context of stellar jets (Falle et al. 1987; Cantó et al. 1989; Raga, Binette, & Cantó 1990; Biro et al. 1993).

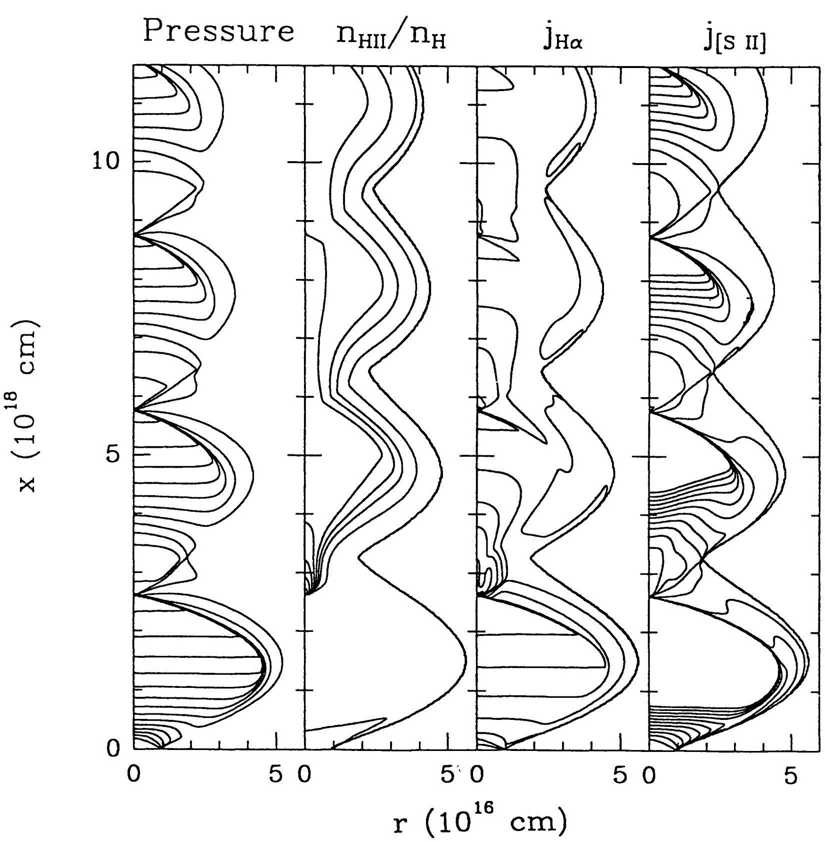

Fig. 1.— Nonadiabatic, axisymmetric, calculation of a steady jet of 200 km s^{-1} velocity and initial jet-to-environment pressure ratio of 30 taken from Raga et al. (1991). The pressure and ionization fraction maps have factor of 2 contours, while the emission coefficient maps have factor of 10 contours.

Even though these crossing shocks are a well-known feature of laboratory jets, many astrophysical jet simulations have been calculated for the case of a jet beam that is in precise pressure balance with the surrounding environment (Blondin et al. 1989, 1990), which supresses the formation of such crossing shocks. However, it is somewhat unclear what is the rationale for this pressure balance condition.

It can possibly be argued that collimation mechanisms based on de Laval nozzle-like flows produce supersonic jets from the acceleration of an initially subsonic flow which is in pressure balance with a stratified medium. However, once the flow has been converted into a collimated, supersonic jet, it can maintain pressure equilibrium with the surrounding environment only if the condition $M_j r_j \ll H$ (where H is the environmental pressure scale height) is satisfied.

For a typical HH jet of radius $r_j \sim 3 \times 10^{15}$ cm and Mach number $M_j \sim 20$ (which are the appropriate parameters for HH 34), we have $M_j r_j \sim 6 \times 10^{16}$ cm. The source in general is surrounded by a cloud core of radius $R_{core} \sim 10^{17}$ cm, and assuming a singular isothermal sphere stratification we have $H = R/2$ (with R being the spherical radius) so that the outer regions of the core have a scale height $H \sim 5 \times 10^{16}$ cm (with even lower values for the interior of the cloud core). From this we would conclude that the condition $M_j r_j \ll H$ is clearly not satisfied for an HH jet emerging from a cloud core.

We therefore have to conclude that if the jet is produced deep inside the core in approximate pressure balance with the surrounding environment, at the point where it emerges from the core into the surrounding ISM it will be highly overpressured. This lack of pressure balance will give rise to a series of steady crossing shocks, such as the ones shown in Figure 1.

So, one of course would be tempted to identify the excitation produced by the crossing shocks with the knots observed along HH jets. Sadly, this is not possible for two reasons. The first reason is that the spacing between the steady crossing shock pairs is $\Delta x \approx 2.8\, r_j M_j$ (see Raga 1989), so that for typical parameters of HH jets (see above) we have $\Delta x \sim 2 \times 10^{17}$ cm, which is comparable to the total length of HH jets. By contrast, the knot spacing of HH 34 is $\Delta x \sim 10^{16}$ cm so that $\Delta x \sim 3\, r_j$, which is a clear problem for an interpretation of these knots in terms of steady crossing shocks. The second reason is of course that high proper motions of $\approx$ 200-300 km s^{-1} have been observed for the knots of HH 34 and HH 111 (which are possibly the best examples of HH jets, see Reipurth 1989). This clearly indicates that these knots do not correspond to stationary phenomena such as the crossing shocks described above.

However, it remains clear that HH jets in al likelihood emerge from molecular cloud cores with a pressure subtsantially higher than the one of the surrounding medium, and will therefore develop a system of crossing shocks. These shocks will be very elongated, and possibly only 2-3 pairs of crossing shocks should be present along the observed lengths of HH jets. Possibly some of the observed features in HH jets might correspond to the excitation produced by these shocks, though this is not the case for the closely spaced, high proper motion knots observed in objects like HH 34 and HH 111.

2.3. Turbulent Mixing Layers

It is a well known result that the lateral jet beam/environment boundary is Kelvin-Helmholtz unstable. The linearized problem for a cylindrical, pressure matched beam gives modes that travel down the beam of the jet. While low radial and azymuthal wavenumber modes extend accross the width of the jet, high wavenumber modes are confined to the region close to the beam/environment boundary (see, e. g., Payne & Cohn 1985). For differing views on the possible relevance of the low wavenumber Kelvin-Helmholtz modes for HH jets see Bodo et al. (1993) and Raga (1994a).

The nonlinear development of the high wavenumber modes gives rise to a turbulent mixing layer, which grows both into the jet and into the environment (see Figure 2). Cantó & Raga (1991), and Stahler (1994) have proposed that the observed molecular outflows might correspond to molecular environmental material entrained into such mixing layers. However, the problem of this interpretation appears to be that the jet beam/environment boundary layer is quite thin (of width comparable to the radius of the jet), so that the predicted molecular outflow has a length-to-width ratio similar to the jet, while observed molecular outflows appear to have considerably lower length-to-width ratios. An even more fundamental problem is that detailed calculations of turbulent mixing layers give very low column densities for most molecular species, so that they should only be detectable in H_2 (Taylor & Raga 1994). This is a direct result of the fact that the mixing layers are so thin.

From this, we would conclude that while the very well collimated, infrared H_2 emission detected in some HH flows (see, e. g., Gredel & Reipurth 1993) might be produced in turbulent mixing layers at the edge of jets, the emission observed in other molecular species probably cannot be explained in terms of such a model. In order to produce, e. g., the observed CO outflows one would need a way of "puffing up" the turbulent mixing layer, so that the momentum of the jet can be transmitted to a larger amount of environmental, molecular gas. In section 3, we will discuss possibilities of how to obtain such an enhanced entrainment rate. A more detailed discussion of mixing layer models is given in the paper by Giovanardi & Lizano (1995) in these Proceedings.

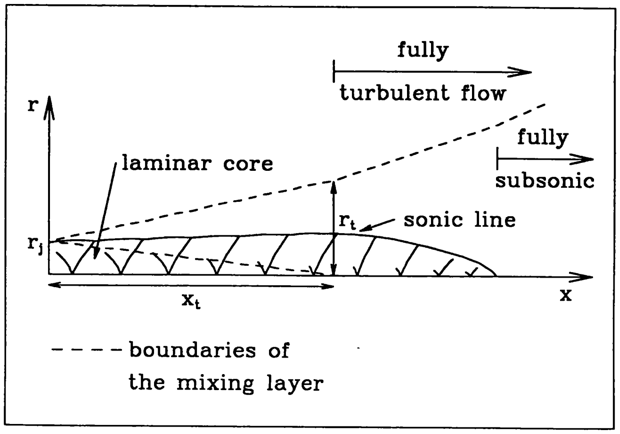

Fig. 2.— Schematic diagram of a turbulent mixing layer at the jet beam/environment boundary, taken from Cantó & Raga (1991).

One should also point out that it has been proposed that at least part of the optical emission of the HH 24 (Solf 1987) and HH 46/47 (Meaburn & Dyson 1987) flows originates in a turbulent mixing layer. The most striking observational results in this context are the "centre-to-limb" velocity and excitation stratification (with highest velocities and lowest excitation on the jet axis) observed in the HH 46/47 flow by Hartigan et al. (1993). Raymond et al. (1994) have successfully interpreted the velocity stratification in terms of a mixing layer model. However, the fact that the excitation (as measured by the Hα/[S II] 6717+31 line ratio) increases outwards from the jet axis is not explained by this model. In section 3.3, and alternative explanation for the HH 46/47 emission (which explains both the velocity and excitation stratifications) is discussed.

2.4. The Head of a Stellar Jet

One of the most interesting features of a jet is the interaction with the environment that takes place at the head of the jet. Because of this, a quite substantial amount of modelling and comparisons with observations of HH objects have been done in this context (see the review of Raga 1994). Numerical simulations showing the structure of the head of HH jets have been done by a number of authors (Raga 1988; Blondin et al. 1989, 1990; Stone & Norman 1993; Gouveia dal Pino & Benz 1993).

The probably most interesting current problems in this context are the modelling (Smith 1993; Curiel & Raymond 1994) and observations (see the review of Reipurth & Cernicharo 1995 in these Proceedings) of infrared H_2 emission in the heads of HH jets and the conjecture that at least part of the emission of molecular outflows might correspond to environmental material pushed by the wings of the bowshock. This identification of molecular outflows with the wings of a bowshock is clearly different from the scenario discussed in section 2.3, where the molecular outflow is associated with material entrained into the beam of the jet. Actually, both mechanisms might be present at the same time, with part of the molecular emission coming from the bowshock wings and part from a jet beam/environment mixing layer.

The analytic and numerical models of Masson & Chernin (1993) and Chernin et al. (1994) appear to elliminate the possibility of coexistence of bowshock wing and mixing layer molecular emission. In these calculations, the post-bowshock material remains in a very narrow, cold shell that detaches from the jet, leaving an empty cavity surrounding the beam of the jet. However, in the more detailed analytic and numerical models of Raga & Cabrit (1994) and Raga et al. (1994), this cavity is actually occupied by low density, molecular gas which can then be entrained into the beam of the jet in a turbulent mixing layer (see Figure 3). The reason for the difference between these two results is not completely clear at the present time, and I would suggest the reader to look at the relevant papers to make a decision on this possibly not so raging controversy.

In order to illustrate the rather extreme complexity of the flow in a non-adiabatic working surface, let me discuss the results obtained from a high resolution numerical simulation. For this simulation, we assume that the axisymmetric jet has a "top hat" velocity cross section (with a velocity $v = 150$ km s^{-1}), and a Gaussian density cross section, going from a peak central density $n = 50$ cm^{-3} to a value of 10 cm^{-3} (equal to the environmental number density) at the outer edge of the jet beam. The beam has a radius $r_j = 3 \times 10^{15}$ cm, and the calculation has been performed on a $10^{16} \times 10^{16}$ cm adaptive grid with 6 levels of binary grid refinement and a maximum resolution of 1.95×10^{13} cm.

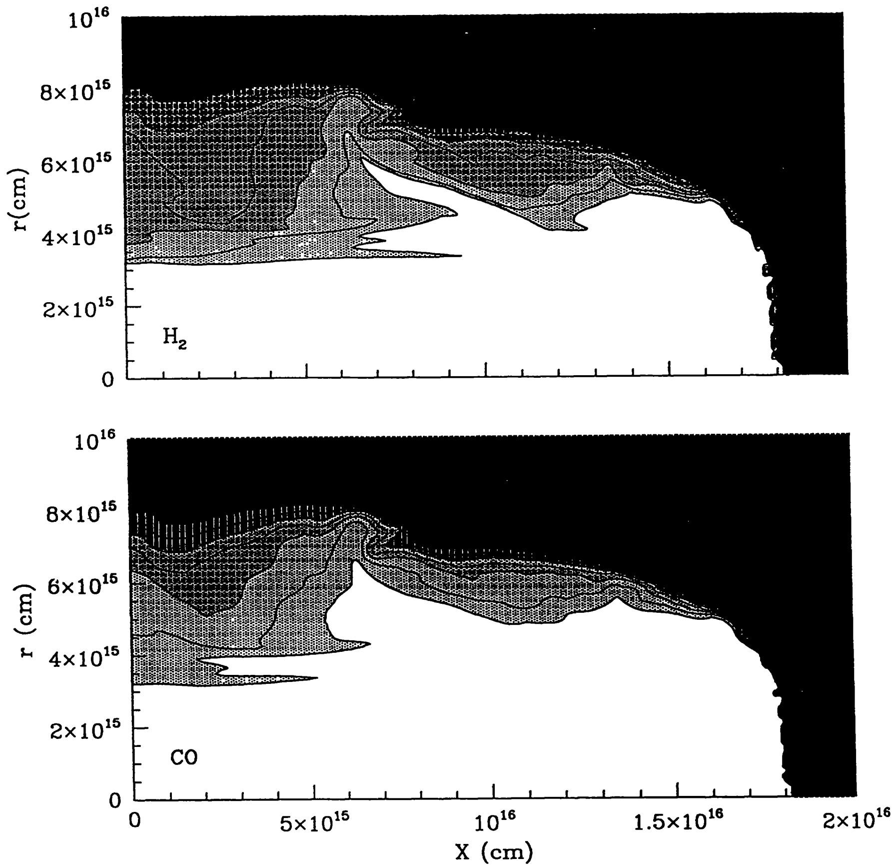

Fig. 3.— Distributions of the fractional abundances of CO (top) and H_2 (bottom) for the working surface of a 130 km s^{-1} jet moving into a molecular environment, taken from Raga et al. (1994). The contours correspond to linear steps of 10% of the peak values of the abundances.

Figure 4 shows a presure time-evolution sequence, computed in a frame of reference moving with the working surface. This choice of coordinate system is achieved by giving an appropriate velocity in the $-x$ direction to the environment. Though being quite complex, this time-evolution can be understood in a more or less straightforward way.

For the parameters given to the jet and to the environment, it can easily be seen that the cooling distances behind the bowshock and the Mach disk are very short compared to the radius of the jet. For example, using the cooling distance interpolation formulae of Cantó et al. (1988), we obtain $d_{cool}/r_j \approx 0.2$ for the bowshock and $d_{cool}/r_j \approx 0.05$ for the Mach disk. Because of this, we would expect the material between the bowshock and the Mach disk to be constrained to a narrow, cool layer.

If the jet beam had "top hat" density and velocity cross sections, we would expect the bowshock and Mach disk to be approximately straight, and that the motion of these two shocks would be determined by a straightforward ram-pressure balance condition. However, in our jet simulation we have a cross section with density decreasing monotonically from the centre to the edge of the beam. It is clear that the layer between the two shocks will then curve, in order to attempt to reach a balance between the environment and jet normal ram pressures and the centrifugal pressure of the curved layer. This curving of the Mach disk/bowshock cool layer can clearly be seen in the first frame ($t = 31.7$ yr, see Figure 4) of the pressure time-sequence.

This curved configuration is very interesting. The environmental material that goes through the bowshock is refracted outwards (toward the bowshock wings). On the other hand, the jet material that goes through the curved Mach disk is refracted inwards (toward the symmetry axis). This results in a pile-up of cool, post-Mach disk material in the stagnation region (see the $t = 63.4$ yr frame in Figure 4).

The formation of this "plug" of cool material was already seen in the much lower resolution simulations of Blondin et al. (1989, 1990), who partially questioned the reality of this feature of their numerical simulations. The present, higher resolution numerical simulations clearly show this feature to be real.

Continuing with the description of the time-evolution, we see that at later times ($t = 95.1$ yr, see Figure 4) the central part of the Mach disk becomes very oblique to the jet beam. This results in a high tangential velocity, which leads to a continuation of the jet flow beyond the Mach disk. This "reborn jet" then pushes out the bowshock, effectively forming a second working surface surging ahead of a now very distorted "main" working surface (see the $t = 126.8$ yr time frame of Figure 4).

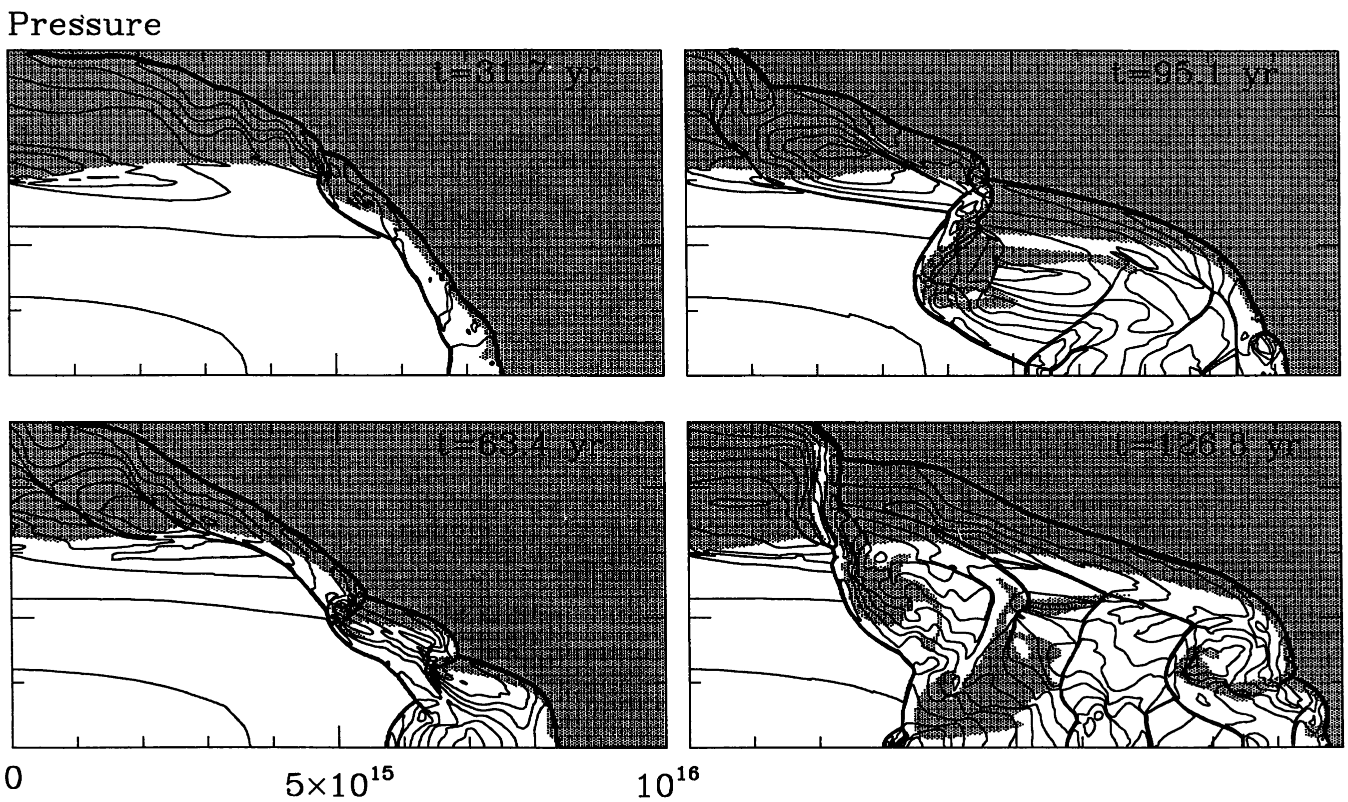

Fig. 4.— Time-sequence of the pressure stratification (with factor of 2 contours) of the working surface model described in the text. The shaded regions are occupied by environmental material.

A prediction of an Hα emission map for the $t = 126.8$ yr time-frame is shown in Figure 5. This map shows a curious structure with a high intensity, compact peak at the position of the "main" working surface, which is preceded by a fainter, spatially more extended bow-shaped feature that corresponds to the head of the "reborn jet". It is probably not necessary for me to remind the connoisseurs among the readers that qualitatively similar configurations are observed in objects like HH 47A and the red-shifted lobe of HH 111.

Finally, one should mention that Figure 4 also shows the regions occupied by environmental (grey) and jet material. From this it is clear that the region of the main Hα peak (see Figure 5) is filled with engulfed environmental material. Because of this, we might expect this region to show H_2 emission, as is observed in HH 47A (see, e. g., Eislöffel et al. 1994).

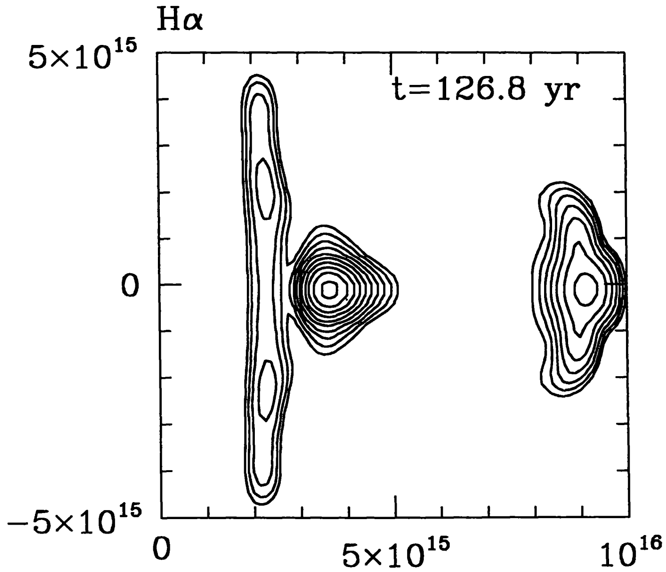

Fig. 5.— Hα image (factor of $\sqrt{2}$ contours) predicted from the simulation shown in Figure 4. A Gaussian smoothing with a FWHM of 5×10^{14} cm has been applied.

3. JETS FROM VARIABLE SOURCES

3.1. General Considerations

There is a substantial amount of recent literature devoted to interpreting the properties of HH flows as a result of a time-variability of the ejection. This point of view had been promoted for some time by observers (see the review of Reipurth & Cernicharo 1995 in these Proceedings), but has been incorporated in models of HH jets only rather recently. Even though these ideas were initially resisted to some extent by "jet theoreticians" (as was clear from the refereeing of the initial paper of Raga et al. 1990 !), they have now been largely accepted, and a number of different groups are exploring the dynamics of HH jets from time-dependent sources.

In the following, an overview of the available calculations of HH jets from variable sources are presented. The cases of a variability in the ejection velocity (*i. e.*, of its magnitude) and direction, as well as a general velocity+direction variability are discussed. This discussion is to some extent an abridged and updated version of the more extensive review on this subject by Raga (1993). The effect of a variability in the density of the jet (at the injection point) is not discussed, since it does not appear to lead to interesting results, at least for the case of high Mach number flows. Finally, the effect of the time-variability on the entrainment of environmental gas is discussed.

3.2. Velocity Variability

Rees (1978) apparently was the first person to suggest that a variability of the ejection velocity might give rise to shock waves in the jet beam, which might correspond to the knots observed in extragalactic jets. Raga *et al.* (1990) realized that for a variability with a highly supersonic velocity amplitude, the shocks formed in the beam would actually be arranged in two-shock "internal working surfaces", and derived numerical solutions to Burgers' equation describing the motion of these internal working surfaces. Kofman & Raga (1992) and Raga & Kofman (1992) then derived analytic solutions of this problem, and Hartigan & Raymond (1993) calculated 1-D solutions with the full gasdynamic equations.

Axisymmetric (Stone & Norman 1993, Falle & Raga 1993, Biro & Raga 1994) and 3D (Gouveia dal Pino & Benz 1994) numerical simulations have been computed with different approximate treatments of the ionization and radiative energy loss terms. Figure 6 shows an example of an axisymmetric simulation of a jet ejected from a source with a sinusoidal velocity variability. The formation of several internal working surfaces is clearly seen.

From the observational point of view, some HH jets indeed show several aligned bow-shaped structures, which can clearly be interpreted in terms of the variable ejection velocity models. However, it is presently unclear whether or not these models can explain the unresolved knots observed close to the source in jets like HH 34 or HH 111. This question might be resolved with future HST observations that do resolve these knots.

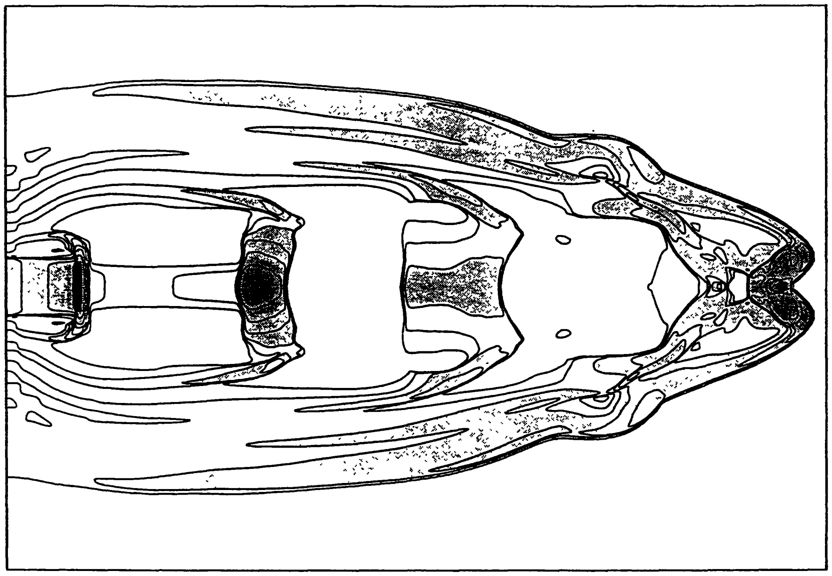

Fig. 6.— Pressure stratification (factor of 2 contours) for a jet with a variable ejection velocity taken from Biro & Raga (1994). The horizontal dimension corresponds to a distance of 6×10^{17} cm.

3.3. Direction Variability

Some HH jets have knots with a consistent lack of alignment, which can be interpreted as evidence for a time-dependence in the direction of ejection. This scenario was proposed by Lightfoot & Glencross (1986) to try to explain the morphologies of many HH objects. Even though some of these authors' interpretations might today seem somewhat over-optimistic, the general idea of a variable ejection direction still appears to be applicable at least for some HH objects.

Raga, Cantó, & Biro (1993) developed an analytic model for the propagation of a quasi-ballistic jet from a source with a variable ejection direction. Biro (1994) has computed two-dimensional nonadiabatic jet simulations of this problem, which illustrate the observational characteristics expected for such a flow. The time-dependence of the ejection direction results in a "garden-hose effect", through which bends in the jet are generated, and amplified at larger distances from the source. This results in a sideways motion of the jet beam through the surrounding environment, which produces a "sideways bowshock" and a corresponding "sideways jet shock" along the leading edge of the side-moving jet beam. These shock pairs are clearly seen in the jet simulation shown in Figure 7 (taken from Biro 1994).

Raga, Cantó & Biro (1993) have shown that the velocity of the post-jet shock material is generally higher than the velocity of the post-bowshock material, so one would expect that the central part of the emitting region (dominated by the emission from the jet shock) would have higher velocities than the off-axis region (dominated by the emission from the bowshock). Also, for a high jet-to-environment density ratio, it can be straightforwardly shown that the jet shock has a lower shock velocity than the bowshock (see Raga, Cantó, & Biro 1993). Because of this, the central regions of the jet emission should have a lower excitation spectrum than the more off-axis regions. This effect is clearly seen in the numerical simulation shown in Figure 8 (taken from Biro 1994).

These properties are clearly qualitatively similar to the observations of Reipurth & Heathcote (1991) and Hartigan et al. (1993) who observed such excitation and velocity stratifications in the HH 46/47 flow. This comparison is clearly appropriate since the HH 46/47 jet shows quite sharp "bends", which approximately coincide with the positions of strongest emission. The interpretation of the emission along HH 46/47 as a result of shocks driven by the sideways motion in this way forms an alternative to the turbulent mixing layer interpretation explored by Raymond et al. (1994).

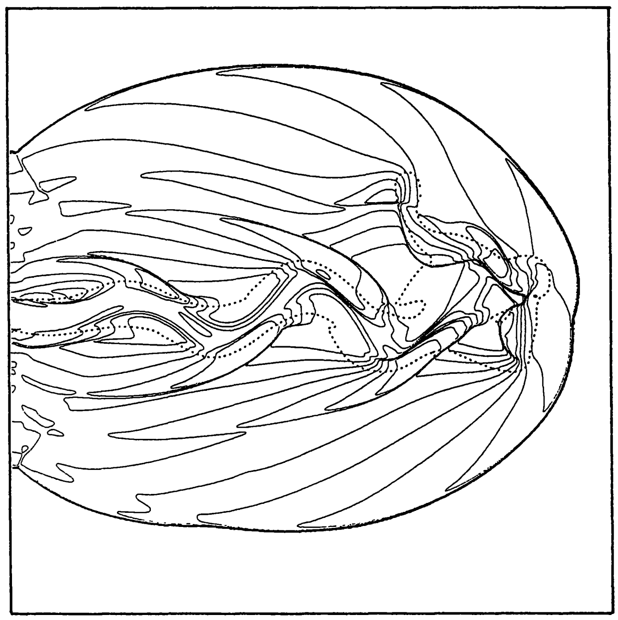

Fig. 7.— Pressure stratification (factor of 2 contours) for a jet with a variable ejection direction taken from Biro (1994). The dashed line represents the jet beam/environment boundary. The horizontal dimension corresponds to a distance of 3×10^{17} cm.

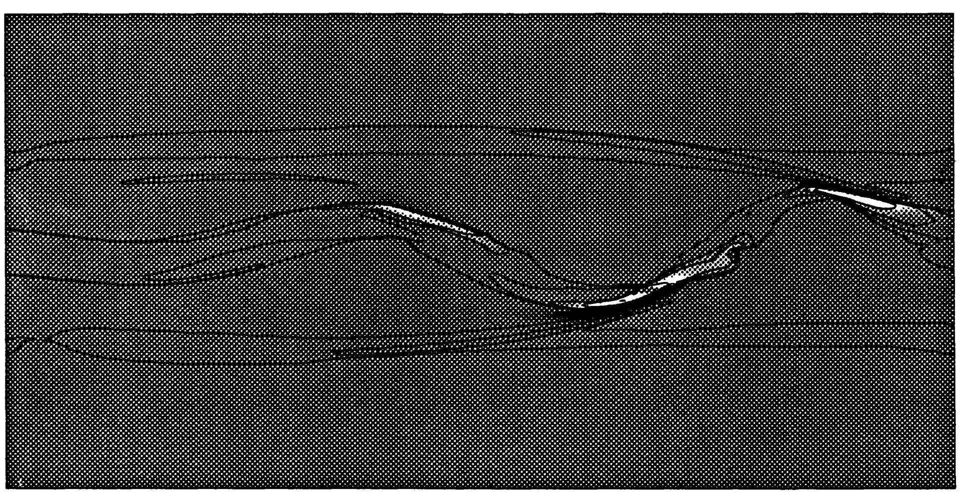

Fig. 8.— Hα–[S II] 6717+31 subtraction intensity map from a nonadiabatic simulation of a jet with a variable ejection direction taken from Biro (1994). The [S II]-bright regions (white) correspond to the emission from the shocks generated in the beam of the jet. The Hα-bright regions (white) correspond to the "sideways-bowshocks" pushed into the surrounding environment. The horizontal dimension corresponds to a distance of 3×10^{17} cm.

3.4. General Velocity+Direction Variability

The effects of a general variability (in both velocity magnitude and direction) of the ejection are very interesting. Raga & Biro (1993) showed both analytically and numerically that such a variability results in the breakup of the jet beam into a number of more or less independent "bullets". Figure 9 (from Raga & Biro 1993) shows the results of a numerical simulation of a 2-D jet, in which the breakup of the jet into bullets is clearly seen.

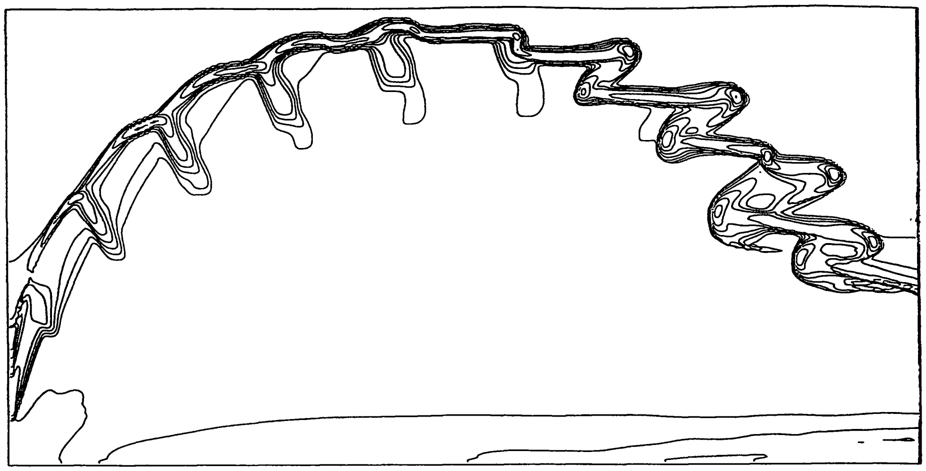

Fig. 9.— Density stratification (factor of 2 contours) showing the breakup of a jet into clumps as a result of a combined velocity magnitude+direction variability, taken from Raga & Biro (1993). The horizontal dimension corresponds to a distance of 10^{18} cm.

This scenario is attractive for interpreting HH flows whith a number of more or less independent, emitting clumps, such as HH 32 (Hartigan, Mundt, & Stocke 1986; Solf, Böhm, & Raga 1986) or the L 1551-IRS 5 outflow (Stocke et al. 1988). From a theoretical point of view, this mechanism for producing high velocity bullets is interesting because it avoids the difficult problem of accelerating high density clumps (without disrupting them) by forming the bullets out of the breakup of an already fast moving jet.

3.5. Effect on the Entrainment

As we have discussed above, a time-dependence of the magnitude and/or direction of the ejection velocity has a rather dramatic effect on the properties of the jet. One of the general characteristics of these effects is that they tend to increase the coupling between the jet beam and the surrounding environment.

For example, "internal working surfaces" resulting from a velocity variability (see section 3.2) eject jet beam material sideways into an "envelope" around the jet. This envelope has a radius that is substantially larger than the jet radius, so that it presents a larger area of contact with the surrounding environment. Raga et al. (1993) have assumed that this envelope can be modelled as a "turbulent jet" formed by a mixture of environment and jet material (ejected sideways by the internal working surfaces). Such turbulent envelopes have a much larger radius (and hence column density) than the turbulent mixing layer around a steady jet (see section 2.3), so that they appear to be much more promising as candidates for producing the emission observed in molecular outflows.

While Raga et al. (1993) considered the average effect of the passage of a large number of internal working surfaces, Raga, & Cabrit (1993) have modelled the detailed interaction between a single internal working surface and an unperturbed surrounding environment. This situation of the theoretical development of the subject is not completely satisfactory, since no clear link exists between these two approaches for modelling the interaction between internal working surfaces and the surrounding environment.

Jets from a source with variable ejection direction enhance the coupling between the jet beam and the surrounding environment by the production of the "sideways bowshock". This bowshock will have low shock velocity wings which might produce part of the molecular emission observed in HH flows. For example, the curved H_2 jet detected by Davis et al. (1994) might be a good candidate for such an interpretation.

Finally, a jet that has broken up into a series of "bullets" will clearly have an enhanced interaction with the surrounding environment through the production of bowshocks associated with the individual bullets. Each of these bowshocks would produce molecular emission in a way similar to the one expected for the leading head of a jet (see section 2.4).

4. JET/CLOUD CORE COLLISION

As discussed by Reipurth & Cernicharo (1995) in these Proceedings, it appears that the HH 110 outflow corresponds to a jet that is deflected through a collision with a dense molecular clump. Theoretically, this problem is analogous to the well studied problem of "wall jets", in which high velocity laboratory jets are pointed at, and splattered against rigid walls. In such flows, it is generally observed that the initial collimation of the jet is almost completely lost after the impact against the wall. The reason for this is that a strong shock is formed close to the point of impact, which produces a strong decrease in the Mach number of the jet (depending on the incidence angle, even to values less than 1), allowing the jet material to expand in all directions.

In the case of HH jets, however, the problem is made more interesting by the fact that the shock formed by the impact against the dense obstacle is likely to be highly nonadiabatic. In these conditions, the lowering of the Mach number is not so dramatic, so that the post-shock flow still retains part of the initial collimation. This problem of the collision of a non-adiabatic jet with an obstacle has been explored analytically (though in a different context) by Cantó et al. (1988), who showed that the velocity v_i of the incident beam, the velocity v_r of the reflected beam and the incidence angle θ follow the relation $v_r \approx v_i \cos\theta$. This relation is satisfied with surprising accuracy by the HH 110 outflow (see the paper of Reipurth & Cernicahro 1995 in these Proceedings).

Figure 10 shows the result of a 2-D simulation of a jet colliding with a dense obstacle (from a new project in which Jorge Cantó and I are working on). This calculation illustrates the fact that the jet survives the collision

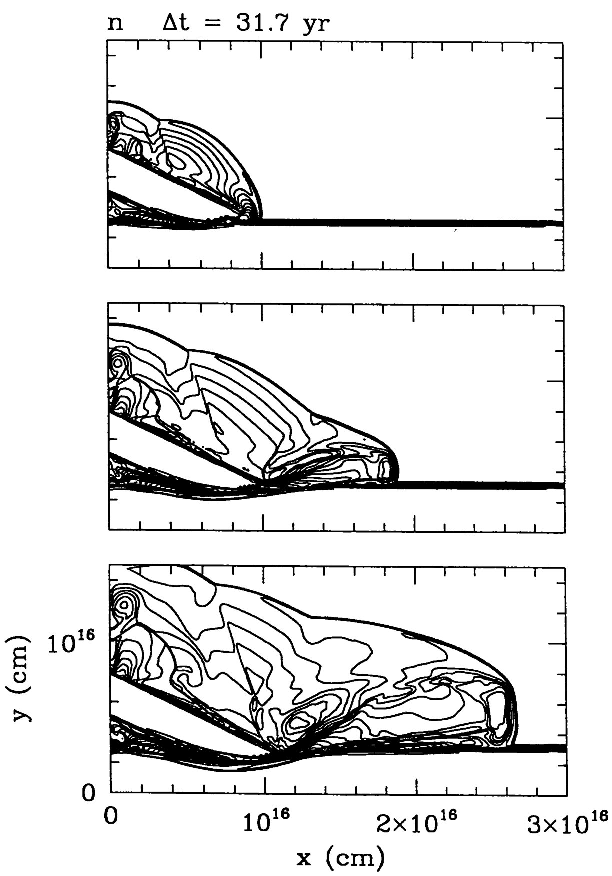

Fig. 10.— Density time-sequence of a v = 100 km s^{-1}, n = 5 cm^{-3}, jet colliding with a plane, n = 500 cm^{-3} "obstacle".

with only a partial loss of collimation. A qualitatively similar loss of collimation appears to be observed in the HH 110 flow (see the paper of Reipurth & Cernicharo 1995 in these Proceedings).

Both the partial loss of collimation of the jet beam and the detailed shock structure are more clearly seen in Figure 11, which shows a blow-up of the jet/cloud collision region.

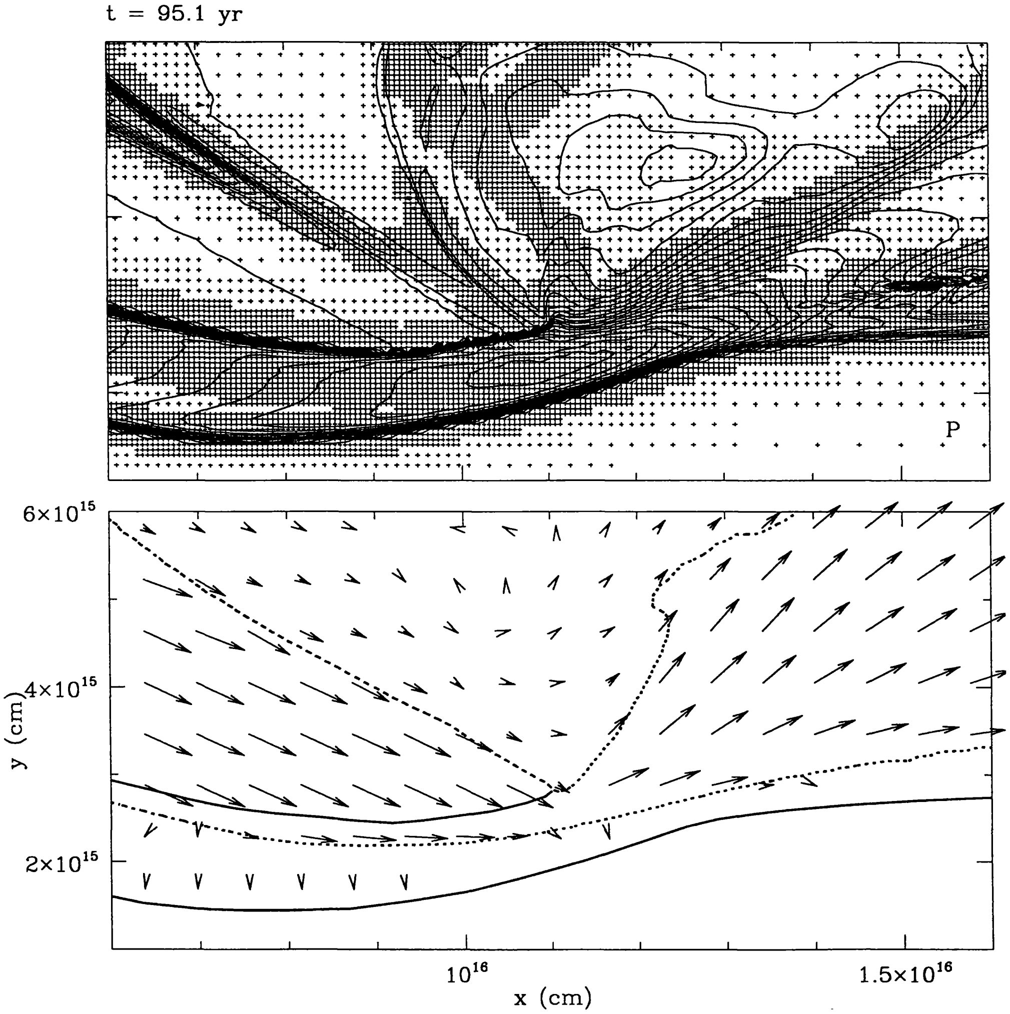

Fig. 11.— Pressure stratification (factor of 2 contours, top) and velocity vectors (largest vectors corresponding to 100 km s^{-1}, bottom) of the jet/cloud collision region. In the bottom plot, the dashed lines correspond to the contact discontinuities at the edges of the jet beam, and the solid lines correspond to the shock waves driven into the jet and into the cloud core. In the upper plot, the crosses show the distribution of points chosen by the adaptive grid algorithm.

5. SUMMARY

This paper has reviewed the current state of models of HH flows and molecular outflows. Throughout the discussion, it has been stressed that both of these phenomena can in principle be explained on the basis of a single-flow "unified model". This of course still amounts to only a conjecture, and the possibility that HH flows and molecular outflows might be independently generated cannot be elliminated. However, effects such as the spatial coincidence of "optical" and "molecular" clumps (see the review of Reipurth & Cernicharo 1995 in these Proceedings) do seem to indicate that at least in some objects a unified model is indeed correct.

The coupling between the (atomic) jet and the (molecular) environment can be achieved through entrainment into a turbulent mixing layer along the beam of the jet (section 2.3) or through the "pushing" that takes place through the bowshock at the head of the jet (section 2.4). These two coupling mechanisms are strongly enhanced by the presence of a time-dependent ejection (section 3.5), which leads to the formation of a number of different shocks driven by the jet into the surrounding environment.

Models of jets from variable sources (section 3) are currently quite popular for explaining the aligned knot and multiple bowshock structures observed in many HH flows (see the review of Reipurth & Cernicharo 1995 in these Proceedings). Given the right combination of velocity magnitude and direction variability, jet flows that break up into a number of "interstellar bullets" can easily be obtained. These models give us the possibility of explaining the widely varying morphologies observed in different HH objects as a result of different time-variabilities of the sources. The longer term survival of these models will hinge on detailed future comparisons between theoretical predictions and imaging and spectroscopic observations of HH objects.

I would like to thank the organizers of the conference for inviting me to give this review talk, and to apologize for having to cancel my trip to Cozumel at the last moment. I am extremely grateful to Prof. John Dyson, who most kindly agreed to give the talk with very short notice, and I am sure gave it more competently than I would have been able to.

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