HIGH-VELOCITY HERBIG-HARO OBJECTS. THE JET INTERPRETATION

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A growing number of oppositely-directed, high-velocity Herbig-Haro objects are currently being discovered in association with young stellar objects. The high degree of collinearity manifested by the velocity vectors in some of these objects provides strong support for the interpretation of bipolar outflows in molecular clouds in terms of highly collimated, supersonic jets. Such jets might form as a result of an anisotropic pressure distribution in the cloud, which could lead to the establishment of transonic de Laval nozzles (see *Ap. J.*, **261**, 115). The jets, in turn, provide a natural framework in which such issues as the energy budget for HH-objects and their location relative to (CO) emission and (optical) reflection lobes can be resolved. In this picture, the HH-objects are interpreted as dense clumps of matter which have been entrained in the jet and accelerated by the flow. The large spread in velocities often found within HH-objects which are observed with a sufficiently high resolution could be attributed to the fragmentation (and subsequent differential acceleration) of clumps which have only recently encountered the flow (or which have recently left the jet and are starting to decelerate). Alternatively, this spread in velocities could correspond to a range of velocities acquired by the clumps near the origin of the jet. In the latter interpretation, the clumps move in pressure equilibrium with the flow, and become visible only when they pass through high-pressure region in the jet, where they are compressed by shocks. The high-pressure regions could correspond to quasi-periodic oscillations in the jet radius which are included by surface instabilities. This interpretation may explain the apparent absence of gradients in the measured proper motions of high-velocity HH-objects, as well as the quasi-periodic distribution of some of these objects. Finally, it is noted that the short travel times ($\sim 10^2$ yr) which are inferred for the outflows associated with these objects imply that the high-velocity outflows are effectively continuous on the time scale ($\sim 10^4$ yr) of the separating CO lobes within which the HH-objects are found.

DISCUSSION

Bok: 1) What fixes the direction in which the jet (or collimation) goes? Is it rotation of the protostar or its magnetic field? 2) Do you expect the embedded protostar to be rotating?

Königl: 1) It could probably be either of the above mechanisms, which in fact may not be unrelated. I would like to note in this connection that in a number of bipolar sources there is evidence (from polarization measurements) that the background magnetic field in the cloud is aligned roughly in the direction of the bipolar axis. 2) The specific collimation mechanism which I have described does not depend on whether the star rotates or not. I expect that in some cases the embedded protostar may still be rapidly rotating, as evidenced by observations of certain T Tauri stars.

Peimbert: Can you make a theoretical prediction as to the separation in seconds of arc between the [O I], [S II] emission and the X-ray or *UV* emission? Is it possible to observe it with present equipment?

Königl: As I noted, if the observed HH-objects correspond to high-pressure regions in the jet, then the shocks (Mach disks) which could accompany the compression of the jet material might give rise to X-ray emission from roughly the same region as the optical line emission (which presumably is associated with the clump shocks). This may explain, for example, the X-ray emission already reported for HH 1. In this picture, the X-ray, *UV*, and optical emission arise from the same general location. The same conclusion would apply if the X-rays arise from the bow shock attached to an accelerating or decelerating clump.

Tenorio-Tagle: HH 1 and 2 and 7-11 are moving in the plane of the sky and both spatially coincide with the maximum in CO and/or formaldehyde emission (see Loren *et al.* 1979, *Ap. J.*, **234**, 932; Evans 1976). Could you comment on how could these possible fit in your interpretation if a decreasing density gradient is required to form the nozzle? 2) The numerical simulations of Norman *et al.*

1981 to reproduce the original model of Bladford and Rees, indicate a poor degree of collimation. I do not see how with the same mechanism you are able to explain the observed clustering of some HH-objects.

Königl: 1) To the best of my knowledge, none of the currently available observations could be interpreted as implying that the position of a given HH-object coincides with the density peak in the cloud. I believe, in fact, that the data generally are consistent with the HH-objects moving along the direction of the steepest density gradient in their vicinity. 2) You are right that the numerical experiments which you quoted indicate poor collimation. These experiments are admittedly idealized, but in any case one would expect the external pressure distribution and/or the internal magnetic hoop stresses in the jet to provide substantial additional collimation.

Choe: Kelvin-Helmholtz instability may not work at the sides of HH-objects because supersonic regions occur at the sides. When HH-objects are decelerating, then we can also consider the Rayleigh-Taylor instability at the front of HH-objects. Thus, you must take account of decelerating HH-objects.

Königl: With regard to your first comment, the suppression of the Kelvin-Helmholtz instability would presumably depend on how efficiently the shocked jet material is accelerated down-stream from the bow shock. As for the Rayleigh-Taylor instability, I certainly agree that it would be important also for decelerating clumps. In fact, the situation in decelerating clumps is, in this respect, identical to that in accelerating ones.

HYDRODYNAMIC-NUMERICAL MODELS FOR HH-OBJECTS

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We present two-dimensional hydrodynamic calculations based on the interstellar bullet mechanism for Herbig-Haro (HH) object formation. This work is an extension of ideas presented by C. Norman and J. Silk (1979, *Ap. J.*, 228, 197). We present results of high velocity cloudlets (bullets) impacting denser, partially ionized interstellar clouds. The bullets have a velocity of 100 km s^{-1} and may or may not be contained in a lower density 100 km s^{-1} wind. One case of a high-speed wind interacting with a cloud cavity is also discussed. Only the high-speed bullet with wind evolves into a possible HH-object.

DISCUSSION

Ho: 1) What are the physics, e.g., viscocity, self-gravity, etc., used in the calculations? 2) What is the effect of bringing the cloud density up by 1-2 orders of magnitude as may be expected from observations?

Sandford: 1) Equations solved are given in the *Ap. J.*, article cited in our paper. Self-gravity is not included. Viscosity is set to 1×10^{-3} for Kg (see SWK, above), but this is less than the numerical viscosity. Viscous effects are not considered important compared to the numerical diffusion that results from the 1st-order differencing used. The details of radiative cooling are important, however. We solve rate equations giving the balance of collisional ionization and radiative and collisional recombination to an average ground state for H. Recombination radiation is removed from the internal energy but details of line cooling and Lyα scattering are not considered. This scheme approximates the correct physics and it is much better than using a steady-state cooling law which gives a completely isothermal limit and can lead to erroneous densities. It may eventually be necessary to include line cooling details to make quantitative comparisons with data. 2) Bringing the bullet density up by one or two orders of magnitude will result in a case that resembles a shock incident upon a step-down in density and we would expect different phenomenology than presented here. This will be discussed in future work, but it is not easy to anticipate the result.

R. Schwartz: Is the ionized region behind the cloudlet identified with a lee shock as found in your previous work?

Whitaker: No, the lee shock in the previous work was on the opposite side of the cloudlet from the wind.

Sandford: The result calculated here is quite different than the case for a wind incident on a cloudlet. The ionized region behind the bullet results from the interaction of the bullet wake and incident wind flows which concentrate and collisionally ionize gas from the target cloud.