# THEORETICAL MODELS OF HERBIG-HARO OBJECTS

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ABSTRACT. A brief overview of the observational characteristics of HH objects is given. Current models for their production by the interaction of stellar winds and jets with interstellar gas are critically discussed. Models for two specific systems of HH objects, namely, the Orion HH objects and the HH46-47 system are described with reference to the general production mechanisms.

## 1. INTRODUCTION

It would be hard to imagine more deceptively uninteresting objects than the inconspicuous semi-stellar knots of nebulosity seen against the dark clouds of NGC 1999 first brought to the attention of the astronomical world independently by Herbig (1951) and Haro (1952). Herbig (1951) realized immediately that their bright [OI] line emission set them apart from the relatively well understood photoionized HII regions, and, with considerable prescience, suggested that their excitation involved some mechanical process which involved stellar participation. Many years later, these seemingly unremarkable objects are the subject of extensive observational and theoretical investigation, and considerable controversy surrounds their interpretation. To some extent, the controversy is artificial, specifically in regard to mechanisms for physically producing these objects, since there has been a marked tendency to look for a unique model to describe what is most probably a collection of objects produced in a variety of ways. This is not to say that these objects do not have features in common, in particular, there seems little doubt that the emission from HH objects is due to the mechanism of shock excitation (though see Section 5.2 for a possible caveat to this statement).

The astrophysical significance of HH objects can hardly be overstressed - at least not in this meeting! Their existence is bound up with the structure and stellar (or proto-stellar) content of dark molecular clouds. Not all that long ago, it would have almost certainly provoked cries of outrage (not least from the author) to suggest that dark clouds are much more interesting than the observationally far more spectacular HII regions. However, the richness of dynamical, physical and chemical phenomena



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occurring in them revealed by radio, infra-red and mm-wavelength investigations over the past few years strongly support this viewpoint.

The study of HH objects has unearthed a number of largely unresolved problems in theoretical astrophysics: for example, the structure of cooling flows behind complex shock structures, the interaction of various forms of stellar mass loss with their environment and, arguably most important of all, the production and collimation of remarkably energetic stellar mass loss from relatively low luminosity stars. This review deals with a restricted sub-set of these problems, namely the gas dynamical interactions which can - possibly - lead to the formation of HH objects. It is not, however, possible - or even sensible - to attempt to discuss these interactions without at least some passing references to the other problems, and these will be made as appropriate.

## 2. OBSERVATIONAL CHARACTERISTICS OF HERBIG-HARO OBJECTS

Extensive discussion of HH characteristics are given by Schwartz (1983), Mundt (these Proceedings) and in the recent Symposium edited by Canto and Mendoza (1983), and only a few salient details will be reviewed here.

Optical spectra imply that a wide range of excitation conditions exist from one HH object to another, and equally importantly, within a given object. Böhm (1983) has compared the characteristic spectrum of a high-excitation HH object (HH2H) with that of a low-excitation object (HH7). Striking differences are apparent; for example strong [OIII]5007Å emission in the former but not in the latter, extremely strong [SII]6724Å emission in the latter, much weaker in the former. Both classes of object show [OI]6300, 6363Å emission, but the emission from this low ionization state ion is much stronger in the latter. Any model of any particular HH object should model its spectrum as well as its kinematics, but there has been a strong tendency to concentrate on this second aspect.

A few HH objects have been detected in the UV, although their close association with the dusty dark clouds clearly militates against this, HH1, 2 and 32 (all classed as high excitation optically) show lines from very high excitation ions such as $C^{+3}$ and $O^{+3}$. The presence of these ions in conjunction with that of, for example, O°, has important implications for the structure of HH objects. Two low excitation objects, (HH43, 47), show UV Lyman band lines of $H_2$, but do not show the high excitation ionic emission seen in the other objects.

Near infra-red observations have also indicated the association of $H_2$ and HH objects. In some cases the molecular emission appears to envelop the object.

A strong blue continuum emission has been observed in some HH objects. Its origin is the subject of debate. It may be two-photon emission from hydrogen, in which case there are very important implications for the structure of shocks in HH objects (Dopita, Binette and Schwarts, 1982). Table I lists various important physical characteristics of HH objects which have been derived from their spectra. In the main they have been taken from Bohm (1983).

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TABLE I

| Parameter | Characteristic Values |
|---|---|
| Scale size (AU) | 300 - 2000 |
| Electron temperature (K) | 7500 - 12000 |
| Electron density ($cm^{-3}$) | $2x10^3$ - $6x10^4$ |
| Fractional ionization | 0.07 - 0.8 |
| Mass (earth masses) | $\sim$10 |
| Filling factor | $2x10^{-3}$ - $7x10^{-2}$ |
| Luminosity (1200-11000Å;$L_\odot$) | 0.1 - 1.4 |

The low ionization fraction immediately rules out photoionization as the source of excitation; the low filling factor is consistent with emission from a relatively thin cooling region behind a shock wave. Shock wave excitation is also indicated by molecular hydrogen line ratios where observed.

The association of HH objects and large scale molecular flows (e.g. Edwards and Snell, 1983, 1984) suggests that whatever powers these flows also may be responsible for the formation of HH objects. Infra-red data has shown that stars (or proto-stars) are the culprits. It also seems beyond doubt that some manifestation of stellar mass loss is the agency of energy or momentum transfer.

It is very important to establish the source of excitation for a given HH object or group of objects, not least because its determination can influence the choice of preferred formation mechanism. Cantó (1985) notes that there can be considerable doubt about the identification, as, for example, in the case of HH12, where three different identification criteria lead to three different excitation sources. HH1 and HH2 have provided a classic example where the obvious exciting candidate, the CS star, has turned out to be an innocent bystander (Pravdo et al, 1985).

The wide range of ionization state noted above implies a wide range of shock velocities within a given object. This can be caused by a mixture of shocks of different strengths and/or by the presence of curved shocks (Hartmann and Raymond, 1984). There is also evidence that some shocks may be very young (Dopita et al, 1982).

The radial and tangential velocities of HH objects can be large, as would be expected for a shock origin. The upper limits of the velocities are about 300 km $s^{-1}$ from proper motion studies, and, for the case of the Orion HH objects, 450 km $s^{-1}$ from line widths. The main kinematic features are discussed by Cantó (1985).

## 3. WIND INTERACTIONS AND THE FORMATION OF HH OBJECTS

### 3.1 General Remarks

The impact of a hypersonic stellar wind (velocity $V_*$, mass loss rate $\dot{M}_*$

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on surrounding gas (density $n_O$) sets up a two shock flow pattern in which an outer shock accelerates ambient gas and an inner shock decelerates the wind. The resultant dynamics is determined by the ratio of the cooling time in the shocked wind to the dynamical timescale. This ratio is greater than one if $V_* > V_c \equiv 250(n_3\dot{M}_6)^{1/9}$ km s$^{-1}$ (Dyson, 1984), where $\dot{M}_6 \equiv \dot{M}_*/10^{-6}$ $M_\odot$ yr$^{-1}$ and $n_3 \equiv n_O/10^3$ cm$^{-3}$. The outer shock is then driven by the pressure of the shocked wind (Case A). If $V_* < V_c$, the shocked wind gas radiates well and the swept-up gas is accelerated by the wind momentum (Case B). This criterion assumes that there is no mixing of cool gas into the shocked wind gas.

Case A: the outer shock velocity $V_O \sim (\dot{M}_* V_*^2/n_O)^{1/5} t^{-2/5}$ and the radius $R_O \sim (\dot{M}_* V_*^2/n_O)^{1/5} t^{3/5}$. Cooling takes place behind the outer shock only, and the total luminosity per unit area of shock is $L_O \simeq n_O V_O^3$ $n_O^{2/5} t^{-6/5}$. Localized HH objects in principle could be identified with post-shock cooling regions as the outer shock encounters higher-than-average density condensations in the ambient gas. The luminosity of an HH object formed in this way would be $L_{HH} \simeq n_O V_O^3 R_O^2 \Omega \simeq \dot{E}_* \Omega t^{-6/5}$ where $\Omega$ is the solid angle subtended at the star by the HH object, and $\dot{E}_*$ is the wind mechanical luminosity. The HH luminosity decays with time.

Case B: the outer shock velocity $V_O \sim (\dot{M}_* V_*/n_O)^{1/4} t^{-\frac{1}{2}}$ and the radius $R_O \sim (\dot{M}_* V_*/n_O)^{1/4} t^{\frac{1}{2}}$. Radiation is now produced behind both shocks and the ratio of the areal luminosities is $L_I/L_O \simeq (V_* - V_O)/V_O \simeq V_*/V_O$. The inner shock luminosity dominates. Localized HH objects again can be produced by high density concentrations of ambient gas and their luminosities would be time indepedent if they are so dense that the local $V_O$ is very low. As noted by Cantó (1979), the outer shock is not necessary in this interaction. It could have degenerated into a sound wave or the flow have reached pressure equilibrium with its surroundings. The HH luminosity would be $L_{HH} \simeq n_W V_*^3 r^2 \Omega$, where the inner shock is located distance r from the star and $n_W$ is the wind density ($\equiv \dot{M}_*/4\pi r^2 V_*$) at r. Obviously, again $L_{HH} \simeq \dot{E}_* \Omega$.

## 3.2 The Schwartz-Dopita Model

Schwartz and Dopita (1980) advanced essentially the Case B interaction above. Figure 1 sketches their model. As previously discussed, the bowshock ($\equiv$ the inner shock) luminosity dominates the total luminosity, however, emission from behind the slow shock driven into the condensation (e.g. molecular or low ionization line) could have observable consequences. The post-shock temperature $T_S \sim \cos^2\psi$ (Fig. 1) and excitation is thus highest in the stagnation zone. Roughly speaking, the excitation would decrease with increasing distance from the star. HH43 (Schwartz, Dopita and Cohen, 1985) appears to be an example of this behaviour. This varying excitation is an important feature of this model and of all models where curved shocks are formed. Hartmann and Raymond (1984) have demonstrated that this mixed excitation emission is one plausible way to produce the wide excitation range demonstrated by optical and UV data.

A variety of arguments can be stated in the context of this model - but which have much more general validity - to show that the wind must suffer a high degree of collimation.

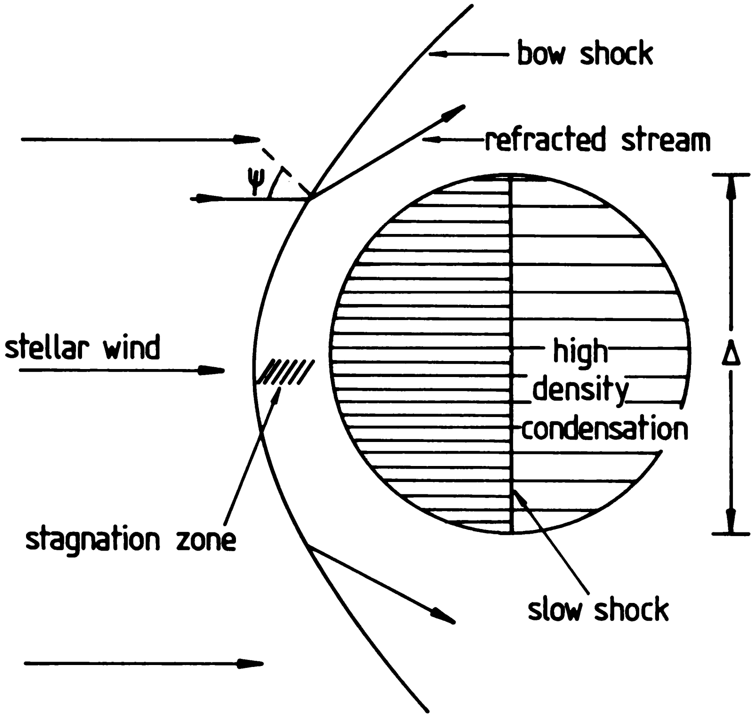


Figure 1. The flow pattern for the impact of a stellar wind on a dense condensation.

The cooling time of the post-shock flow must be less than the flow time around the condensation, otherwise the shocked wind gas will expand without cooling. This condition translates into the mass-loss rate requirement $\dot{M}_6 \gg 0.03 V_1{}^5 r_{0.1}{}^2 \Delta_1{}^{-1}$, where $V_1 \equiv V_*/100$ km s$^{-1}$, $r_{0.1} \equiv r/0.1$ pc and $\Delta_1$ is the scale size $\Delta$ of the condensation in units of 1000 AU. Kahn's (1976) cooling approximation has been used. Very high mass loss rates are needed to satisfy this requirement for reasonable $V_1$.

Secondly, the maximum post-shock compression is about $(V_*/C_o)^2$, where $C_o$ is the sound speed ($\simeq$10 km s$^{-1}$) in the cooled emitting gas. A characteristic HH density of $10^4$ cm$^{-3}$, say, requires $\dot{M}_6 \simeq 40 r_{0.1}{}^2/V_1$ (for a spherical wind).

The final argument is well illustrated by HH43. The luminosity of HH43 is about $0.2L_\odot$, whereas the luminosity of the exciting star (IRS 1) is about $5L_\odot$ (Schwartz et al, 1985). Using the geometrical parameters given by Schwartz et al (1985), the stellar mechanical luminosity needed is $\dot{E}_* \simeq 40L_*$ which, for $V_1 \simeq 2$, say, gives an implied mass-loss rate of $\dot{M}_6 \simeq 60$.

There are other strong observational grounds which imply collimation of the wind, notably the association of bi-polar CO flows and HH objects. Liseau and Sandell (1986) have demonstrated convincingly the real association of these two phenomena.

A particular difficulty with this model is the production of HH objects which have a high proper motion. Hydrodynamic calculations (e.g. Nittmann, Falle and Gaskell, 1982) have shown that the maximum velocity which can be given to the condensation as a whole is about equal to the slow shock velocity $V_s \simeq (n_w/n_c)^{\frac{1}{2}} V_*$, where $n_w$ and $n_c$ are respectively the pre-shock wind and condensation densities. In general, $V_s \ll V_*$ because of the high density contrast.

Many aspects of this model pose interesting and largely unanswered questions. It is known (.e.g Innes, 1985) that shocks of velocity greater than about 150 km $s^{-1}$ are unsteady because of the thermally unstable post-shock cooling. The entire post-shock zone is likely to be unsteady and turbulent. Further, mixing in of cold condensation material via, for example, the process described by Hartquist et al (1986) may significantly affect the emitted spectrum as a result of charge exchange (Hartmann and Raymond, 1984). This mass addition can also strongly affect the dynamics of post-shock flow (Hartquist et al, 1986).

### 3.3 The Norman-Silk Model

Norman and Silk (1979) suggested that the break-up of a cocoon about a star by the action of a stellar wind would lead to the production of fast moving interstellar bullets which would plough through the interstellar medium driving bow shocks into the ambient gas. The cooling flows behind these shocks would be the HH objects. (The flow pattern in this model is essentially that of the S-D model in a different frame of reference). Three major observational differences between this and the S-D model are immediately apparent. Firstly, the bulk of the emission should occur at roughly the bullet speed and high proper motion HH objects are automatically produced (unless the object moves predominantly parallel to the line of sight). Secondly, the excitation sense is opposite to that of the S-D model; the highest excitation should be seen furthest away from the exciting source (e.g. HH1 and 2). Thirdly, shocked molecular emission could arise behind the more oblique parts of the shock if the interstellar gas contains molecules and could envelop the optically visible HH object. The remarks above regarding unanswered questions which can be addressed to the S-D model are equally applicable to the Norman-Silk model.

Cantó and Rodriguez (1986) have presented evidence in favour of this model, at least with regard to HH2. They find that the measured electron density in the components of this object fit the relationship $n_e \sim V_T$, where $V_T$ is the total component velocity (radial velocity + proper motion velocity). This is most simply explained in terms of the motion of a shock of velocity $V_T$ into a medium containing a magnetic field $H_o$ strong enough to dominate the pressure in the post-shock cooled gas. If this is the case, $H_o^2 \sim V_T^2$ and, for a 1-D field compression, $H \sim n_e$, thus giving the observed correlation.

There are serious difficulties with the formation mechanism for the bullets as originally proposed (see Section 3.2). In an attempt to circumvent the problems, Tenorio-Tagle and Rozyczka (1984) advanced a mechanism which depends upon the focussing of large scale wind or explosion driven shocks by obstacles in their path. A converging conical shock is produced which can lead to the formation of bullets provided that gas shocked by the conical shock cools fast enough. An attractive feature of this model is that, in principle, the bullets can outstrip the main shock, and about 50% of HH objects seem to lie outside the boundaries of the associated molecular flows. However, a very serious difficulty with this model is its critical dependence on the maintenance of strict geometrical constraints. The converging shock must be conical and completely uniform. It is very hard to see how these constraints can be satisfied in what is undoubtedly an extremely irregular ambient medium.

(The jet 'working surface' model (Section 4.2) is an extension of this, but instead of bullets hurled by a one-off impulse, the bullets have continuous momentum transfer to them).

### 3.4 The Cantó Model

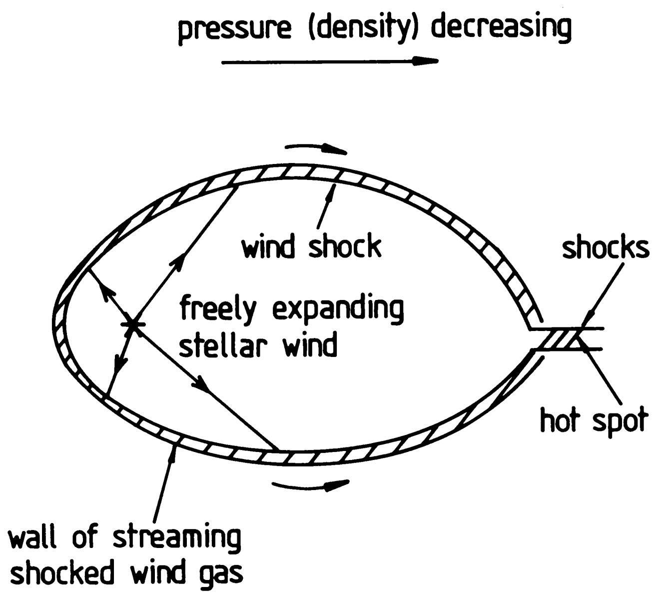


Figure 2. The excavation of a cavity in an interstellar cloud by a stellar wind which cools on shocking.

Cantó (1980) recognised the severe energy problem associated with HH objects and suggested that if some means of focussing the winds could be arranged, the difficulty could be removed. His suggestion was to use the focussing properties of density gradients in the gas around the wind source (Fig. 2). Provided that the shocked stellar wind gas cools well, a stationary state can be realised in which shocked wind gas is in pressure equilibrium with the ambient gas. An ovoid cavity whose walls are defined by standing shocks in the stellar wind is excavated in the surrounding gas. Because the ambient gas has a non-uniform pressure, the shocks are oblique, the wind streamlines refract across them and the shocked gas flows around the cavity walls. The flowing gas stream can converge to a

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focus. Cantó (1980) suggests that HH objects can be identified either with bright patches on the walls, or, most efficiently, with emission at the focal point. The cavity shape is determined by the choice of density distribution. A symmetric distribution leads to a two-lobe cavity. It is very tempting to link this morphology to that of the bi-polar molecular flows. Cantó (1985) has advanced a possible way of doing this. The flowing gas streams are supposed linked to the surrounding molecular gas by viscous coupling. However, the physical details of the coupling mechanism remain to be elucidated.

The structure of the focal point depends critically on the obliquity of the shocks through which the gas flows into this point. If these shocks are more or less normal to the flow, a stationary HH object would be produced which has no proper motion but which has a line width comparable to the velocity of the colliding streams. Very oblique shocks could produce a similar (though presumably rather lower excitation) object, again with no proper motion unless some means of re-exciting the cooled gas occurs. The cooled gas could, given the right geometry (e.g. Tenorio-Tagle and Rozyczka, 1985), take the form of a jet which could give rise to HH objects as discussed in Section 4.1, with or without proper motions. Cantó (1985) has also hypothesised that that gas injection into the focus may be in the form of clumps which could drive bow-shocks ahead of themselves into surrounding gas and produce HH objects in the way described by Norman and Silk (1979).

Although this model has the great virtue of efficiency, there are some difficulties with it. Firstly a static configuration is set up in a time-scale about equal to that for changes in the external density distribution to occur. Secondly, and perhaps most importantly, the external density distribution must be extremely smooth.

### 3.5 The Königl Model

Königl (1982) considered the other extreme case of a wind blowing into an inhomogeneous distribution, but where the wind does not cool after shocking. Here, the shocked wind expands and forms a De Laval nozzle which points down the density gradient. HH objects are supposed to result from the acceleration of clumps of material produced, for example, by the detachment of portions of the wall. The collimation of the flow again produces some increased efficiency over the spherically symmetric case. Problems with this model include the difficulty in acceleration of clumps by gas streams, the necessity of having a smooth external density distribution, and finally, there may be stability problems with the subsonic section of the nozzle.

## 4. JET INTERACTIONS

### 4.1 General Remarks

Mundt and Fried's (1984) startling discovery of jet-like structures associated with T-Tauri stars has generated a new cottage industry for HH production (see Cantó (1986) for a dissenting view). A review of the jet properties - at least as far as is presently surmised - is given by Mundt (1985). We start off here with the basic premise that, somehow, stars produce high Mach number jets which are collimated at least down to a distance of about 1000 AU from the stars, and discuss general ways in which the interaction of jets with their surroundings can give rise to emission features which might be identified as HH objects.

Wilson and Falle (1985) have described how steady jets propagating into non-uniform surroundings set up internal shock structures. The jet tries to come into pressure equilibrium with the ambient gas, but cannot do so if $L_p < L_s$, where $L_p$ is the length scale for pressure variations in the surrounding medium and $L_s$ is the distance moved by the jet fluid in the internal sound crossing time in the jet. $L_s \simeq V_j R_j / C_j \equiv M_j R_j$, where $V_j$ and $C_j$ are respectively the jet velocity and internal sound speed and $M_j$ is the internal Mach number. Shocks are set up if $L_p < M_j R_j$, and if the sense of adjustment to the pressure variation is to decrease the opening angle of the jet (or if it goes through a maximum). High Mach number jets are more susceptible to shock formation than low Mach number jets. In principle, this internal shock structure can contain oblique shocks and normal shocks (Mach discs). As a general rule, the shock obliquity increases and the Mach disc size decreases with increasing jet Mach number. This mixture of shocks should produce a wide range of excitation. Falle, Wilson and Innes (this meeting) have made the first attempt to match this type of structure to chains of HH objects, specifically to HH7-11.

In the steady case, HH objects which result from cooling behind internal shocks in jets cannot have high proper motions. Unsteady jets can also have internal shocks which can be set up in a variety of ways (Norman, Smarr and Winkler, 1984), and in this situation the shock pattern will move, perhaps then giving rise to proper motions.

Supersonic jets can entrain material from their confining surroundings (e.g. De Young, 1986). If internal shocks are present in the jet, this gas could be excited into emission by the hot jet material with similar spectral consequences to the mixing process suggested for HH2 (Hartmann and Raymond, 1984). An intriguing possibility is that this mixing process could lead to a supersonic turbulent boundary layer if, during the mixing process, the local cooling time becomes less than the sound crossing time for the mixing zone. Shock-shock collisions could dissipate kinetic energy ultimately leading to the relatively show collision of streams of dense gas and thus favour low excitation emission (Kahn, private communication). There is some evidence of boundary layer phenomena occurring in the HH46-47 system (Section 5.2).

## 4.2 The 'Working Surface' Model

At the head of the jet, the 'working surface', shocks occur in both the jet gas and the ambient gas. The structure is shown in Figure 3 (adapted from Smith et al, 1984). Dyson (1984) and Mundt (1985) independently proposed that HH objects could be produced in gas cooling behind either of these shocks. HH objects would trace the path of the working surface as the jet bores through the interstellar gas. The velocity of the working surface, $V_s$, is determined by momentum balance at the jet head and is

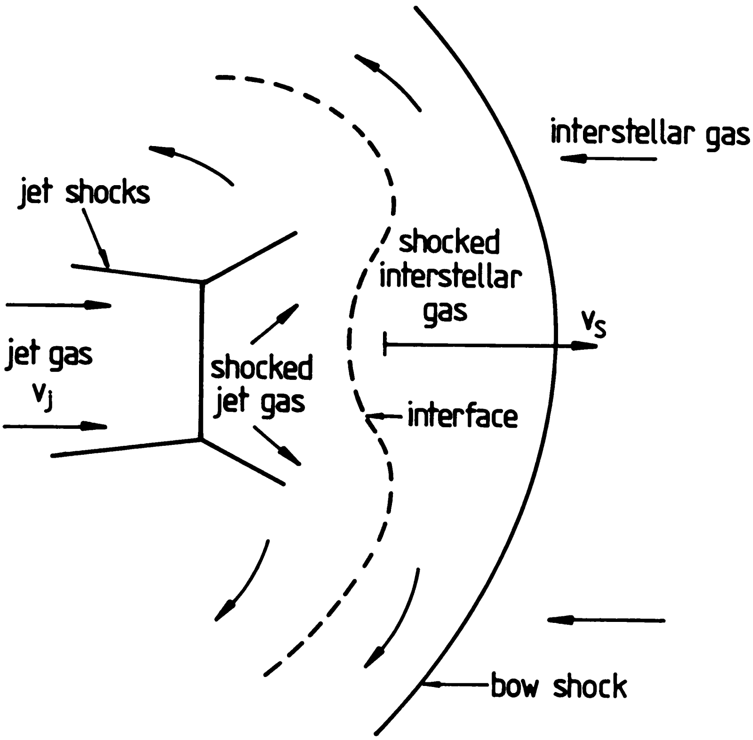


Figure 3. Schematic drawing of the working surface of a jet as it bores through ambient gas.

approximately (Dyson, 1984) $V_S \simeq (11/r_{0.1}\theta)(\dot{M}_6 V_j/n_3)^{\frac{1}{2}}$, where $\theta$ is the jet opening angle (in °) and $V_S$ and $V_j$ are expressed in units of 100 km $s^{-1}$. As a suitable example, $V_j = 3$, $n_3 = r_{0.1} = 1$, $\dot{M}_6 = 0.1$, $\theta = 10°$ gives $V_S \simeq 0.6$ and $V_j - V_S \simeq 2.4$. Cooling shocked ambient gas will produce a much lower excitation emission spectrum than cooling shocked jet gas. The wide range of excitation conditions observed in some HH objects can be produced in this way. The spatial distribution of the emission will be complex. Roughly, for emission behind either shock, the excitation will be highest furthest away from the star. This will be observed if emission from either shock dominates. However, the lower excitation shock is furthest from the star. The spatial distribution of excitation will not be so simple if emission comes from behind both shocks. It is likely that the emitting region will be clumpy because of thermal instabilities and/or Rayleigh-Taylor instabilities (cf. Allen and Hughes, 1983).

Provided, of course, that the angle of the jet to the line of sight is not too small, HH objects produced in this way will automatically possess proper motions. Since $V_j > V_S$ always, very high proper motions (>300 km $s^{-1}$, say) require very high jet speeds. This requirement, together with other evidence (e.g. the very high 450 km $s^{-1}$ velocities measured for the Orion HH objects - Section 5.1), suggests that at least some HH phenomena involve extremely high wind or jet velocities, maybe as high as 1000 km $s^{-1}$.

Reipurth et al (1986) have drawn together many of the ideas of Sections 4.1 and 4.2 to model the HH34 system. They argue that HH34 itself is produced by the working surface. The short bright jet near the proposed exciting star could be produced by internal shocks in a jet confined by a dense gas cloud around the star. The jet may originate on a stellar or circumstellar scale. Alternatively they suggest that the jet is produced at the focal point of a flow collimated as in Cantó's (1980) model (Tenorio-Tagle and Rozyczka, 1985).

## 5. TWO PARTICULAR CASES

In this section we briefly discuss two associations of HH objects, the Orion HH objects and the HH46-47 system, in the light of the more general discussion above.

### 5.1 The Orion HH Objects

Axon and Taylor (1984) discovered nine high velocity condensations on the front surface of OMC1 which had rather similar spectral characteristics to HH objects. The investigation of the kinematics of these objects was substantially extended by Taylor et al (1986) - henceforth TDAH. Very high blue shifted line wings (up to 450 km $s^{-1}$ from line centre) were observed in the [OI] 6300 Å lines. A very significant feature of this data is the invariable accompaniment of these extended line wings (the HVC) by narrow enhanced [OI] emission (the ZVC) at the systemic nebular [OI] velocity.

This latter feature, together with the extended spatial distribution of the HH objects places severe constraints on possible models for their production. It is, for example, hard to see how the Cantó model can produce several focal points. The bulk of the emission on the Silk-Norman model should be produced at the bullet velocity and not at the systemic nebular velocity. TDAH have discussed the relationship of the objects to current models in some detail.

If the HH objects are produced by the cooling of a wind impacting on dense condensations of ambient gas (cf. the Schwartz-Dopita model), arguments on the cooling time demand that the wind be collimated into a jet. The necessity that the jet produce isolated HH objects simultaneously visible over an extensive region of the sky led TDAH to propose a precessing jet model. HH objects are produced by the cooling of jet gas as it shocks against isolated very dense condensations of ambient gas. This precession might indicate that the likely excitation source, IRS2, is a binary system. Interestingly, Lightfoot and Glencross (1986) have proposed a model for the HH7-11 system which also involves a precessing jet.

Although the HH objects seen in Orion emit strongly in [OI], this in itself does not necessarily mean that they are shock excited. Strong [OI] emission can be produced in the ionization front separating an HII region from an HI region. In view of this, TDAH proposed an alternative model

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for the Orion objects which utilizes a wind which needs some degree of collimation, but must be spatially extended enough to power the HH objects simultaneously. In this model, the stellar wind impacts on the rear (neutral) faces of dense intrusions in the ionization front which separates OMC1 from the ionized Orion nebula. The ionization fronts on the faces of these condensations illuminated by the exciting stars of M42 are the sites of the ZVC. The stellar wind detaches small clouds of material from the dense intrusions and accelerates them out of the 'shadows' of the intrusions into the stellar UV radiation field. Provided the small clouds are optically thick in the Lyman continuum, they too have surface ionization fronts which emit in [OI]. This latter requirement essentially fixes the wind mass-flow rate. The fast moving clouds must be very small and a large assemblage of such clouds (resembling an aerosol spray) must be present. There are some serious unanswered questions involved with this latter mechanism, for example relating to cloud acceleration and survival in the hot shocked wind which, in this model, does not cool on shocking.

TDAH note that objects formed by either model might occur in other molecular clouds/HII region interface regions.

## 5.2 The HH46-47 System

Meaburn and Dyson (1986) have presented recent observational data on the Hα and [SII] 6716, 31 Å line profiles along the emission line filament HH47B which connects HH46 and HH47A. A remarkable result is that the Hα profile across HH47B is broad (∿100 km $s^{-1}$), and that the associated [SII] profile shows a distinct splitting over the same velocity range. It appears that the emitting volume contains Hα emitting gas throughout, but [SII] emitting gas at the boundary only.

Meaburn and Dyson (1986) have proposed a jet interaction model to describe the system. They interpret HH46 as shocks in the jet nozzle, HH47A as the working surface of the jet, and HH47B as being produced by internal shocks in the jet. For an (admittedly arbitrarily chosen) inclination angle of the jet to the sky of 30°, they derive a jet mass through-put rate of $\dot{M}_6 \simeq 0.02$ and a jet speed $V_{j_3} \simeq 1.8$. The ambient density ahead of the working surface is about 7 $cm^{-3}$, suggesting that the jet has reached the outer low density regions of the cloud. They propose that the [SII] emission results from surface phenomena on the jet, perhaps assoicated with entrainment of mass. The velocity separation of the [SII] peaks implies that there is considerable deviation of the direction of the gas velocity at the jet boundary from simple radial motion along the jet.

As is well-known, HH47A and HH47B have extremely low excitation spectra. In the case of HH47B this could be due to pronounced obliquity of the internal shocks and/or the mixing-in of neutral material at the jet boundary. The estimated velocity of the working surface is $V_s \simeq 1.4$ (Meaburn and Dyson, 1986). Hence $V_j - V_s \simeq 0.4$. The low excitation spectrum of HH47A may be due to the mixing in of partially ionized shocked jet gas with fully ionized shocked ambient gas. This system provides an excellent example of the proposition that the kinematics cannot be divorced from the spectral characteristics.

## 6. DISCUSSION

In spite of the large volume of observational and theoretical work of the last few years, there is no concensus of opinion about the way in which HH objects are formed. This is really not surprising if HH objects represent the cooling regions behind shocks. If stellar mass loss sets up any form of supersonic flow, shocks will inevitably appear somewhere in it. The only criteria which have to be satisfied are that somewhere, the post-shock cooling time is less than the dynamic timescale of the flow and that the shocks are fast enough to cause the necessary excitation. The necessary conclusion of this is that HH objects or systems of objects should be treated on an individual basis and that to look for a universal flow interaction to explain them all is not a profitable procedure.

The areas for future work are extensive. For example the calculation of the spectra of non-steady shocks with and without post-shock mixing of cool or hot gas is clearly necessary. Very little work has been carried out on the boundary layers and cocoons associated with jets as they traverse the ambient gas. The calculation of the structure of very high Mach number jets ($M_j > 10$) is another important area. Increasing evidence that precessing jets may be present also presents interesting possibilities. No mention has been made above of the possible role played by non-continuous stellar mass loss (e.g. the FU Ori phenomenon). The relationship of the bright jets, the HH objects and the large scale molecular flows remains largely a mystery. Perhaps stars have winds and jets simultaneously. A final, and in many respects, most fundamental area for future work, is to understand why stellar jets are there in the first place.

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