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THEORETICAL MODELS FOR HERBIG-HARO OBJECTS

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ABSTRACT. Since the time of their discovery, HH-objects have been the subject of extensive observational studies and intense theoretical work. At present the general consensus is in the sense that they represent shock waves of about 100 km s^{-1} running in a dense, nearly neutral medium with density $\sim$ 100 cm^{-3}. This review summarizes current models for the general scenario of the origin of these objects which result in the formation of shock waves with characteristics similar to those observed in HH-objects. Some models regard the objects as the result of an eruptive event from a T Tauri star most likely an FU Ori phenomenon. Other models interpret the objects in terms of wind-accelerated clumps of material interacting either with a stellar wind or with the ambient medium. There is contradictory observational evidence favoring both alternatives. In particular, direct correlations between the total spatial velocity of individual subcondensations in HH2 and their physical parameters such as electron density, the surface brightness and size, favor the latter interpretation.

I. INTRODUCTION

The prototypes of the HH-object class were discovered by Herbig (1951) and Haro (1950, 1952) more than thirty years ago. Since that time these objects and many other members of this class have been the subject of extensive observational studies from X-rays to radio frequencies. These observations have provided a vast amount of empirical information about the objects themselves and their molecular environment motivating, at the same time, intense theoretical work which attempts to explain the nature of these peculiar objects.

Theoretical studies on HH-objects may be divided into two major categories: those dealing with the problem of the excitation mechanism and those which are concerned with the fundamental question of their physical origin.

II. EXCITATION MECHANISMS

Studies of the physical state of HH-objects and their excitation mechanism started, back in the late fifties, with the spectrophotometric studies of HH1 by Böhm (1956), Osterbrock (1958) and Haro and Minkowski (1960). From them it was learned that simple ionization mechanisms such as photoionization from a central source or collisional ionization by thermal electrons within the emitting region could not be the dominant excitation mechanisms. The electron temperature indicated by relative intensities of the forbidden lines ($\sim 10^4$ K) was too low to produce any significant ionization. Photoionization from a central source, on the other hand, would predict an emission in the [O I] and [S II] much lower than the observed one.

Following Herbig's (1951) idea, Osterbrock (1958) later suggested that ionization in HH-nebulae could be the result of the deceleration of high-energy particles ejected from a hidden T Tauri-like star. Back to this idea were the close physical and spectral similarities between the prototype HH-nebulae and the small emission nebula close to T Tauri, together with some indications that T Tauri was losing mass at high velocities (∿ 100 km s^{-1}).

This idea was explored by Magnan and Schatzman (1965) and also by Gurzadyan (1974, 1975) who considered the streaming of high energy charged particles through a neutral dusty medium. In order to account for the degree of hydrogen ionization an extremely high energy for the incident particles was needed, ∿ 1 MeV.

Further developments in the search for the excitation mechanism in HH-objects did not occur until 1974 when infrared observations of several HH-objects and their surroundings were undertaken by the Stroms and coworkers (Strom, Grasdalen and Strom 1974; Strom, Strom, and Kinman 1974). These observations did not reveal any star at the position of HH-objects; instead, embedded IR sources typically displaced within one light year from the optical object were discovered. These IR sources were interpreted as the exciting stars of the optical nebulae since broadband optical polarization in two condensations of HH24 indicated a reflection origin from the displaced IR source. It was then suggested that HH-objects were nebulae produced by reflection from a pre-main-sequence star deeply embedded in the parent cloud.

This interpretation, however, encountered serious difficulties when Schmidt and Miller (1979) showed that the strong polarization observed in HH-24 was mainly due to the underlying red continuum. The emission lines, which define the HH-class, were found to be essentially unpolarized. This indicated that although the red continuum is likely to be originated by reflection, most of the light in HH-objects is produced *in situ*.

By that time there was growing observational evidence indicating that the emitting material in HH-objects was moving supersonically with respect to its sorrounding (Strom, Grasdalen, and Strom 1974). This fact, combined with the great similarity between the spectra of HH1 and the SNR N49 in the LMC led Schwartz (1975) to suggest that the line emission in HH-objects is produced in the cooling region of a fast shock wave. Furthermore, Schwartz (1975) revived the idea that the energy source of HH-objects was a strong stellar wind. Radiating shocks at the interface between the wind and the interstellar medium could produce the observed spectra.

Final support for the idea that the characteristic emission of HH-object is produced in the cooling region of a shock wave was given by the shock wave calculations of Raymond (1976, 1979), Dopita (1978) and Shull and Mckee (1979). Approximations to the optical spectra of HH1 and 2 were obtained with pre-shock densities of about 300 cm^{-3}, shock velocities in the range 70-100 km s^{-1}, solar abundances, and low fractional pre-shock ionization.

Recently, however, detailed studies in the *UV* and *IR* of several HH-objects have revealed spectral features which cannot be reproduced by the same shock models which account for the optical spectrum. Nevertheless, the general consensus is in the sense that emission in HH-objects is in fact produced *in situ* by shock waves running in a dense, nearly neutral medium, although a much more complex situation must be involved.

Models which attempt to explain the excitation in HH-objects as a result of a shock wave can be classified in two groups: those in which an eruptive or blast event from a central source is assumed, and those in which the more or less continuous action of a stellar wind is proposed.

III. MODELS INVOLVING AN ERUPTIVE EVENT

In this group we have Böhm's (1978) model, in which each condensation within a particular object represents a spherical blast shock wave propagating outwards through the ambient medium. Considering as typical values 10^3 cm^{-3} for the ambient density and 50 km s^{-1} for the shock velocity the observed variability time scale, size and filling factors of condensations are reproduced. The model requires a central source providing an initial energy input of about 10^{42} erg within each condensation. However, this model does not explain the alignments of HH-objects with IR sources, as well as the large and organized proper motions observed in several of them.

Also along this line Gyulbudagyan (1975) and Dopita (1978) suggested that the HH-objects could be the result of an eruptive FU Ori event in a low luminosity star. This possibility could provide an attractive explanation to the apparent energy problem indicated by the present association of some powerful HH-objects with rather weak activity low luminosity T Tauri stars. Known FU Ori stars have reached luminosities of $\sim 10^3$ $L_{\odot}$ with the ejection of shells at velocities of $\sim$ 100 km s^{-1}, fading afterwards gradually. Therefore, it may be argued that HH-objects are the result of a past eruptive event undergone by the associated star at present of low luminosity. However, it remains to be shown if such an event does in fact produce nebulae with the characteristics observed in HH-objects.

IV. MODELS INVOLVING A STELLAR WIND

Models which consider the continuous action of a wind as the energy source of HH-objects can also be divided into two groups according to the aspect of the problem that is emphasized. Those which are mainly concerned with the acceleration of the surrounding medium by the action of the wind and those which study possible mechanisms for channeling or focussing the wind before the production of the optical objects themselves. Models within each category are not exclusive but complement each other in many respects.

Before we actually comment on these models it is necessary first, to summarize briefly the dynamical interaction of a T Tauri-like wind ($\dot{M}_* \sim 10^{-8}$ $M_{\odot}$ yr^{-1}, $V_* \sim 300$ km s^{-1}) with the ambient medium and then discuss the models within this context.

a) *Evolution of a wind-driven bubble.*

The dynamical history of the expanding system produced by a T Tauri-like wind can be divided in three or four phases (Norman and Silk 1980). It begins with an initial phase of free expansion at the wind velocity, lasting for a few years until the wind sweeps up an interstellar mass comparable with its own. At this time the flow structure consists of four regions: (a) the unshocked stellar wind region, (b) a region of shocked stellar wind, (c) a shell of shocked ambient gas,and (d) the motionless interstellar medium. Regions (c) and (d) are separated by a shock which accelerate the ambient gas. At the boundary between regions (a) and (b) there is also a shock which decelates the wind (Dyson 1981).

Although this structure remains unaltered during most of the subsequent dynamical evolution of the system, its detailed development depends on whether cooling of the shocked gases is important or not.

Just after the formation of this pattern, radiative losses in both socked gases are negligible and each region behaves adiabatically. This phase lasts only for a few years since the shocked interstellar gas cools down very quickly collapsing into a cool thin shell. The flow structure then enters into a phase of evolution that depends strongly on the velocity of the wind (Norman and Silk 1980).

For wind velocities $\gtrsim$ 100 km s^{-1}, the shocked stellar wind region remains hot, because of its rather inefficient cooling, and the flow pattern then consists of a thin shell of interstellar material being pushed by a nearly isobaric bubble of hot gas which fills most of the inner volume. This evolutionary stage lasts for about 10^4 years, until the hot interior cools and the pressure driving the shell falls. Then, the inner shock separating regions (a) and (b) overtakes the outer shell and the wind impacts directly on this region. The radius of the shell continues to grow until equilibrium with the surroundings is reached, a few times 10^4 yr later.

For wind velocities $\lesssim$ 100 km s^{-1} radiative cooling always prevails in the shocked stellar wind, and a hot bubble of shocked wind is never formed. The flow pattern always consists of a growing shell of shocked material (both wind and interstellar) being pushed directly by the wind. The dynamical evolution of the system ends when pressure equilibrium with the surrounding medium is reached.

Independent of the wind velocity, the final static configuration consists of a cavity, filled by unshocked stellar wind and bounded by a shock in it. This configuration is maintained by the wind ram pressure as long as the wind blows.

b) *Cloudlets Models*.

Several years ago Schwartz (1975) and later Norman and Silk (1979) and Rodríguez *et al.* (1980) considered the possibility that HH-objects could represent the interaction of clumps of material with either the wind or the surrounding medium.

In Schwartz' (1975) view (see also Schwartz and Dopita 1980) there is a central wind source interacting with a medium consisting of discrete dense clumps surrounded by a less dense material. As the wind blows, the tenuous medium is swept up, leaving the clumps exposed to the direct action of the wind. Due to their much higher density, the clumps resist the action of the wind and are accelerated outwards much more slowly. The wind creates a bow shock around the front side of each cloudlet which persist until the cloudlets have been substantially accelerated. These shocks are identified with HH-nebulae.

If the wind is isotropic, mass loss rates in the range 10^{-6} to 10^{-5} $M_\odot$ yr^{-1} are required in order to provide enough kinetic energy to excite the nebulae.

The model proposed by Norman and Silk (1979) and Rodríguez *et al.* (1980) is similar to Schwartz' cloudlet model but is based on the idea, first proposed by Dopita (1978), that the clumps are the result of the breaking-up of a protostellar cocoon (Kahn 1974). Also they differ in the interpretation of the HH-nebulae. The Norman-Silk-Rodríguez model was constructed in order to explain not only the HH-nebulae but also the masers frequently observed in the same region. It starts by assuming a protostellar object which develops a strong wind (or radiation pressure) which interacts with the still infalling cloud material. The interface between the flows is Rayleigh-Taylor unstable and clumps of dense material are formed. The clumps continues to fall toward the protostar until the ram pressure of the wind sweeps them outwards. The subsequent acceleration of the clumps is similar to that in the cloudlet model. However, the clumps considered here are thought to be much more compact and dense since they are expected to be the source of water maser emission for which densities in the range 10^7- 10^{11} cm^{-3} are needed. The heat input for this emission is provided by Kelvin-Helmholtz instabilities generated at the interface between the clumps and the wind. As in the cloudlet model the clumps are also expected to reach high velocities comparable to that of the wind. Eventually the clumps emerge into the cloud at supersonic velocities. At this stage their molecular hydrogen density drops below that required to maintain maser conditions but luminous bow shocks preceding the condensations are formed. The ambient gas is heated and accelerated through these shocks to velocities similar to those of the condensations. Radiation emitted by cooling of this shocked gas become observable as an HH-object.

The two models just described are based on three assumptions deserving some attention. First that the wind is able to impact directly upon the cloudlets. Second that the cloudlets survive the erosive action of the wind, and third that there is an efficient transfer of momentum from the wind to the cloudlet.

For an isotropic wind running in an isotropic medium, direct impact of the wind on cloudlets far from the star is only possible after the hot bubble phase has ended; that is once the inner hot gas has collapsed into a thin shell or once the static configuration has been reached. However, if the wind is highly collimated, for instance by the jet mechanism proposed by Königl (1982) (see below), this condition is likely to be fulfilled at almost any time. The second and third assumptions have to be tested through extensive hydrodynamical calculations since those carried out by Sandford and Whitaker (1982) indicate that little acceleration of the cloudlets may be expected.

c) *Focussing/Channeling Models.*

It is now quite clear that if the HH-objects are produced by the action of a stellar wind, this wind must be highly anisotropic up to the distances where the optical nebulae are produced. This is mainly indicated by the linear alignments of HH-nebulae with their exciting sources, the proper motions and by the bipolar molecular flows frequently associated with them. Also, anisotropic stellar winds reduce substantially both the stellar wind energy and momentum requirements imposed by the luminosity and spatial velocity of the optical objects permitting, in this way, a low mass young star to be the energy source of HH-objects, as suggested by the empirical evidence.

Cantó (1980), Cantó and Rodríguez (1981) and Barral and Cantó (1981); and more recently Königl (1982) have studied possible focussing/channeling wind mechanisms occurring when an originally isotropic wind interacts with a non-uniform surrounding medium with cylindrical symmetry. In particular they considered the case of an isotropic wind source immersed in an interstellar dense disk.

Although both models assume an interstellar disk as the wind focussing/channeling agent, they apply to two different stages of evolution of the wind-driven system.

Königl (1982) proposes a wind channeling mechanism which applies to high velocity winds during the hot bubble phase of evolution. He considers a spherically symmetric wind expanding in a medium with anisotropic density and pressure distributions. In this case, the bubble does not remain spherical but elongates in the direction of decreasing external density and pressure. If the external density distribution can be approximated by a power law in radius with exponent close to 2 (which is likely to exist in protostellar environments) the elongating bubble becomes unstable to the formation of a de Laval nozzle. Once the nozzle has been formed, the hot wind is channeled through it and is accelerated to supersonic velocities (of the same order than that of the wind itself). In particular, for dense disk distributions around the wind source, the formation of two oppositely-directed supersonic jets is obtained.

As in Schwartz cloudlet model,HH-objects with large proper motions are interpreted as dense clumps of matter that have been accelerated by the jets. The clumps could be formed in several, non exclusive, ways. They may be portions of the jet's walls which were torn off by interface instabilities or the result of thermal instability in the subsonic region or simply represent dense condensations of cloud material intercepted by the jet in this path.

An interesting additional feature of this model is that it may also explain the high velocity molecular (bipolar) outflows frequently associated with optical HH-objects. Königl (1982) proposes that the high velocity molecular emission arises in the shocked ambient material that is swept up by the expanding bubble or by the advancing jet. However, it remains to be shown if this interpretation can actually produce the observed properties of the high velocity molecular line emission, such as line shapes, densities, temperatures, etc.

A rather different interpretation of this high velocity molecular outflows is that advanced by Calvet, Cantó and Rodríguez (1981) and developed by Cantó, Torrelles, Calvet, and Rodríguez (1983). They proposed that the force driving the molecular material is viscous coupling with a high velocity wind stream. Preliminar calculations show that this mechanism does in fact produce line shapes similar to those observed.

Cantó (1980), Cantó and Rodríguez (1981) and Barral and Cantó (1981) have considered the focussing of an originally isotropic wind during the next phase of evolution of a wind-driven bubble, that is, when cooling of the shocked wind becomes dominant. In this case, both shocked materials, wind and interstellar, are confined to a thin shell which is pushed directly by the wind.

In the presence of a steep pressure gradient, the shell elongates in the decreasing direction. The shell is still formed by two layers of shocked material separated by a contact discontinuity and bounded by two shocks. Since the inner shock is oblique the wind is strongly refracted across it. Only the normal component of the wind velocity is thermalized and the emergent shocked wind retains an appreciable fraction of its initial momentum and energy. This results in the formation of an annular stream of shocked wind sliding along the walls of the cavity towards the distant extreme of the configuration. The pressure difference between the inner and outer sides of the annular stream increases along the cavity (because of the stream centrifugal pression) and thus, the flow turns towards the axis of the cavity. Close to the axis, the stream is forced to move radially away from the star, but, since the flow is generally supersonic, such a change in direction has to be accomplished through a shock. The final result is a cylindrical stream of hot shocked wind material, moving directly away from the star at large spatial velocities which represents the HH-nebula.

As it stands, this model does not predict large proper motions in HH-objects, since they only represent the cooling region through which the gas flows. In steady state this region remains fixed in space.

It is interesting, however, that this objection could also lead to an attractive explanation to one of the most peculiar properties of HH-objects. That is that although different knots of an HH-object show very different cross motions, the whole object appears rather compact. This characteristic could indicate that the knots were formed very near the site where we see them now.

In the context of the model we may consider the possibility that the focussed stream is formed, not by a continuous flow but, by a group of clumps of condensed material. They may be either due to thermal instabilities in the flow or produced upon interaction with the surroundings. In any case, the result would be the continuous injection of high velocity dense clumps into the ambient gas; this occurring at a fixed point in space. The subsequent interaction with the surrounding will finally stop the clumps not far from the injection point. As in the Norman-Silk-Rodríguez' model, condensations of an HH-object would be represented by luminous bow shocks preceding the moving clumps.

Perhaps the most serious objection to this model is that in some cases the HH-objects are not seen at the tip of the lobes defined by the high velocity molecular outflows which are thought to delineate the wind filled cavity. In some cases this may be due to projection effects.

V. FINAL REMARKS

As we have seen, practically all models of HH-objects attempt to explain them in terms of clumps of material interacting either with the accelerating wind or with the decelerating ambient material. These two opposite alternatives predict, in fact, opposite observational features. In particular that concerning the sense of correlation between the velocity of the object and the velocity of the shock which gives rise to the emission. For clumps which are decelerated by the ambient material the shock velocity is that of the clump itself and therefore, high shock velocity would correlate with high velocity for the emitting material. For clumps accelerated by the wind, the correlation should be in the opposite sense since the shock velocity is the relative velocity between the wind and the cloudlet. Observations should decide between the two alternatives. Unfortunately however, it appears that there is observational evidence favoring both alternatives.

Schwartz and Dopita (1980) suggested that an inverse correlation exists, because of the apparent lack of HH-objects with high radial velocities either showing high excitation or having high electron density back in the cooling region. The excitation state within the object is estimated by the ratio [O III]λ5007/[O I]λ6300, while the electron density is obtained from the ratio λ6717/λ6731 of [S II]. Both quantities are expected to increase with shock velocity.

In complete contrast with this result, there are the direct correlations found by Cantó and Rodríguez (1983) for individual condensations within HH 2. In this unique case, there is available spectroscopic, radial velocity and proper motions information for each individual condensation.

Combining the available data Cantó and Rodríguez found that:

(1) there is no correlation at all between the excitation parameter of Schwartz and Dopita (1980) with the total (radial plus tangential) velocity of condensations;

(2) electron density *increases* with velocity, $\propto V$;

(3) the surface brightness in Hα uncorrected for reddening increases with velocity, $\propto V^2$; and finally,

(4) there is some indication that condensations with higher total velocities have bigger optical sizes.

Correlations (2) and (3) are quite striking. They are what one would expect if each condensation in HH2 represent a single shock wave with velocity *equal* to its spatial velocity ($\sim$ 100-300 km s^{-1}), all moving in a same medium (same pre-shock density and magnetic field) and subject to the same amount of extinction. This interpretation contrast with the results of shock wave modelling of the optical spectrum of some of these condensations which indicates much lower shock velocities, between 70-100 km s^{-1}.

We must notice that, if the interpretation given to correlations (2) and (3) is correct, it strongly favors models in which HH-objects represent clumps of material moving supersonically into the ambient medium. This interpretation is also consistent with correlation (4) since bigger clumps are expected to be more massive and therefore to decelerate more slowly.

VI. SUMMARY

1) Shock wave modelling of the optical line spectra of HH-objects indicates shock velocities in the range 40-100 km s^{-1}, pre-shock densities of about 100 cm^{-3} and low fractional pre-shock ionization. However, the *UV* lines in HH 1 and 2 are indicative of $V_S \sim$100-110 km s^{-1}, while the H_2 infrared lines are characteristic of 15 km s^{-1} shocks.

2) Current models for HH-objects involving shock wave excitation may be divided in two groups: those in which an eruptive event from a central source is assumed, and those in which the

more or less continuous action of a stellar wind is proposed.

3) The present association of some powerful HH-objects with rather weak activity low luminosity T Tauri stars indicates that the most likely eruptive event would be the FU Orionis phenomenon. However, it remains to be shown if such an event does in fact produce nebulae with the characteristics observed in HH-objects.

4) If the HH-objects are produced by the action of a stellar wind, this wind must be highly anisotropic up to the distances where the optical nebulae are produced. Originally isotropic winds can be focussed or channeled upon interaction with a non-uniform surrounding medium with cylindrical symmetry. This is the case for interstellar dense disks.

5) Practically all wind models of HH-objects attempt to explain them in terms of clumps of material interacting either with the accelerating wind or with the decelerating ambient material. There is contradictory observational evidence favoring both alternatives.

6) In particular it is found that each condensation in HH2 appears to represent a single shock wave with velocity *equal* to its spatial velocity ($\sim$ 100-300 km s^{-1}), all moving in the same medium and subject to the same amount of extinction.

7) This, together with some indication that condensations with higher total velocities have bigger optical sizes, strongly favors models in which HH-objects represent clumps of material moving supersonically into the ambient medium.

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DISCUSSION

Liseau: Would you expect to detect the stellar wind from the inside of the bubble at continuum radio wavelengths as an H II region?

Cantó: No. I would expect those kind of winds to be neutral or if ionized to have a quite small emission measure.

Böhm: Would the fact that Herbig and Jones find very different velocities for the individual condensations in the same HH-object (e.g., in HH 2) not also favor the assumption that the shock waves are due to the interaction of blobs of matter with the ambient gas (and not the stellar wind)?

Cantó: In some sense, yes. But I would say that this peculiarity of HH-objects is perhaps indicating that the clumps are formed very near the site where we see them now.

Montmerle: In the flow you are describing, there must be Kelvin-Helmholtz (stream) instabilities at the boundary between the wind and the surrounding material. Could these give rise to the formation of "globules" on the sides of the nozzle? Indeed, one could conceivably thereby explain why you observe both shock directions (with respect to the globules): one direction for the globules still inside the nozzle, and the other direction for the outside globules.

Cantó: This could be an attractive mechanism for the formation of HH-objects and deserves to be explored in more detail. Although Kahn (*Astr. and Ap.*, **83**, 303, 1980) had shown that the instability between the flows does not grow substantially.

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