PART I
YOUNG OBJECTS

https://doi.org/10.1017/S0252921100069141 Published online by Cambridge University Press

HERBIG-HARO OBJECTS

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Summary . The available observational information on the geometrical structure, emission line and continuous spectra, line profiles, radial velocities and linear polarization of Herbig-Haro objects is briefly reviewed. We emphasize the inhomogeneous structure of the "classical" Herbig-Haro objects and the appearance of small "condensations" with radii of $\sim$ 300-900 a.u. The apparent paradox of the presence of "gaseous nebula type" as well as "reflection type" Herbig-Haro objects is discussed.

A purely empirical model of the regions of line formation is discussed. It shows that regions of low density ($N_e \sim 10^3$ cm^{-3}) cover the space between the condensations and most of the volume of the condensations themselves. Only between 0.1 and 1% of the volume of the condensations is covered by a high density medium ($N_e \sim 4 \times 10^4$ cm^{-3}, $N \sim 10^5$ cm^{-3}) which, however, contributes very strongly to the formation of the spectrum.

Different theoretical models for the line forming regions are discussed. We strongly favor the shock wave theory in which the emission lines are formed in the cooling regions of (running) shock waves. The general agreement between observations and the new calculations by Raymond is emphasized, and the few remaining discrepancies are discussed. The possibilities of explaining other properties of Herbig-Haro objects (including time scales, sizes and filling factors of condensations) are described.

1. Introduction

Herbig-Haro objects are small nebulae which often show a very inhomogeneous structure with typical knots (or condensations) having a diameter of the order of only 1000 a.u. or even less (cf. Herbig 1974).

As pointed out by Herbig (cf. 1962, 1969, 1974) Herbig-Haro objects occur only in heavily obscured regions in which also other very young

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objects (especially T Tauri stars) are present. In his 1974 catalogue Herbig lists 41 known Herbig-Haro objects. To this we have to add a number of objects discovered by Strom and his collaborators (cf. Strom, Grasdalen and Strom 1974) and by Schwartz (1977). Though some Herbig-Haro objects show a connection with infrared objects (the best case being HH 24,see Strom, Strom and Kinman 1974) or with a H_2O maser (see Lo, Morris, Moran and Haschik 1976) in many cases we do not see any object which might be considered a "central star" or the "energy source" of the Herbig-Haro object. This is especially surprising in the case of the brightest and the best studied objects HH 1 and HH 2 near NGC 1999.

On the other hand, we have the case of Burnham's nebula which has the spectroscopic properties of a Herbig-Haro object (Herbig 1950, Schwartz 1974, 1975) but definitely has a central star (namely T Tauri). It looks as if the visible presence or non-presence of a central energy source is not decisive for the existence of a Herbig-Haro object.

All these facts must be of considerable importance for our eventual understanding of Herbig-Haro objects. The fact that HH objects appear only in regions where T Tauri stars are present shows that they are young objects. The apparent absence of a "central star", or, more generally, a central energy source has been emphasized already by Haro and Minkowski (1960). I do believe that the existence of extreme density fluctuations and the typical appearance of relatively short-lived (to $\sim$ 10)years) condensations (knots) with radii of a few hundred a.u. is also a fundamental fact relevant to any attempts of theoretical explanation. However, it is also true that some HH objects do not show such a structure but look rather diffuse (Strom, Grasdalen and Strom 1974),

2. Variability

It is generally believed that all Herbig-Haro objects are variable. However, detailed investigations are available for only HH 1 and HH 2 (Herbig 1969, 1973). These studies seem to show time scales of (very roughly) 10-20 years and brightness changes of at least 4^m. There seems to be no clear indication of any systematic relation between the variation of different condensations of a single HH object. It looks as if the individual condensation is really an independent

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entity which varies independently of other events in the same HH object. However, we have to admit that at present the observational material is rather limited and it is not impossible that this conclusion will be changed in the future. If our present conclusion about the independent variability of individual condensations should be confirmed this must certainly have important implications for the theoretical description of HH objects.

Eventually we would of course like to understand the brightness changes in terms of changes of physical parameters like electron temperature, electron density, filling factor, etc.

Some very preliminary studies of this relation have been made (Böhm, Perry and Schwartz 1973, Böhm, Siegmund and Schwartz 1976, see below).

3. Spectra

a) Line Spectra

The spectra show mainly emission lines plus a very faint continuum or quasi-continuum (Herbig 1951, Böhm 1956, Haro and Minkowski 1960, Böhm, Perry and Schwartz 1973, Strom, Grasdalen and Strom 1974, Böhm, Schwartz and Siegmund 1974, 1976, Schwartz 1976).

Emission lines of H, HE I, [N II], [O I], [O II], [O III], [Ne III], Mg I, Ca II, [Ca II], [Cr II], [Fe II], [Fe III] have been observed. Though the spectra show a certain similarity to those of other gaseous nebulae, they also show a number of unusual features. The most outstanding of these are:

(1) The large fluxes in the neutral lines, especially in the [O I] 6300 and 6364 lines with λ 6300 often being stronger than Hβ.

(2) The great strength of the red (6717/31) and of the blue 4068/76 [S II] lines.

(3) The simultaneous presence of the permitted H and K lines and of the forbidden 7291, 7324 lines of Ca II.

(4) The presence of a large number of faint to moderately strong [Fe II] and [Fe III] lines.

A great step forward towards the understanding of these unusual spectra was made by pointing out that they are rather similar to those of some supernova remnants (Osterbrock and Schwartz 1974, Schwartz 1975). This lead immediately to the (preliminary) identification of cooling regions behind shock waves as the places of origin of the emission lines.

In Table I we list the observed lines in the NW part of HH 1 (which is probably the best observed part of any HH object). The data are taken from Böhm, Perry and Schwartz (1973), Böhm, Siegmund and Schwartz (1976) and Schwartz (1976). Whenever scanner observations (from the MCSP at the 200 inch telescope or the image-tube scanner at the 120-inch telescope) are available for strong lines we use these and ignore the image tube measurements (Böhm et al. 1973). Apart from this rule the fluxes given in Table I are found by simple averaging, giving all observations the same weight. In cases in which the individual components of a multiplet could not be resolved in the scans we have determined the line ratios from the image tube plates and normalized the total flux of the lines of this multiplet to the value given by the scanner observations. In Table I we have also listed the line fluxes in the supernova remnant N 49 as measured by Osterbrock and Dufour (1973) in order to show the general agreement. (See also Schwartz 1975). However, we have to admit that there are also some discrepancies especially in the [O II] and [O III] lines. Numbers in brackets indicate uncertain measurements.

It has been pointed out by Böhm and Schwartz (1973), Böhm, Siegmund and Schwartz (1976) and by Schwartz (1976) that different condensations of single HH objects do not show identical spectra (at least in the case of HH 1 and HH 2). These differences are of course only quantitative. Unfortunately, it is not yet known whether and in which way the observed brightness variations are related to time changes in the spectrum.

It is worth noticing that though by far the strongest contributions to the total spectrum of an HH object come from its condensations a faint emission line spectrum is visible in the regions outside of the condensations. (Böhm et al. 1973, Böhm et al. 1976, Schwartz 1976, 1977).

The observed Doppler shifts are quite intriguing. There is a very strong preponderance of negative radial velocities (Strom, Grasdalen and Strom 1974). Some extreme cases are HH 11 with -150 kms^{-1} (Herbig 1962b) and M 42 HH 1 with -240 kms^{-1} (Münch 1977) whereas the average value seems to be of the order of -50 kms^{-1}

Table 1

Relative Emission Line Fluxes in HH1 and N49

Line Ident.	λ_o	F(HHI)	F(N49)
[O II]	3726.2	46	(648)
[O II]	3728.8	174	
H_{12}	3750.0	2	
H_{11}	3770.8	3	
H_{10}	3797.9	4	(27)
H_9	3835.1	7	
[Ne III]	3868.7	10	
H_8	3888.8	7	
Ca II	3933.7	17	(16)
Ca II+H_ϵ	3968.5	22	(41)
	3970.1		
[Fe III]	4046.4	4	
[S II]	4068.6	51	36.1
[S II]	4076.2	18	
H_δ	4101.8	24	36.4
[Fe II]	4114.5	6	
[Fe II]	4244.0	8	8.7
[Fe II]	4244.8		
[Fe II]	4276.2	3	
[Fe II]	4287.4	8	6.1
H_γ	4340.5	46	51.5
[Fe II]	4359.3	10	(4)
[Fe II]	4414.5	18	6.7
[Fe II	4416.3		
Mg I	4571.1	10	4.9
[Fe III]	4658.3	6	7.4
H_β	4861.9	100.	100.
[O III]	4959.5	13	39.8
[O III]	5006.8	38	95.5
[Fe II]	5158.0	18	17.5
	5158.8		

Line Ident.	λ_o	F(HHI)	F(N49)
[N I]	5198.7	14	8.3
	5200.7		
[Fe II]	5261.6	7	6.8
[Fe II]	5273.1	4	4.7
[Fe II]	5333.7	4	1.8
[Fe II]	5376.5	2	--
[Fe II]	5527.3	3	1.5
[O I]	5577.4	3	--
[N II]	5754.8	4	2
[O I]	6300.2	143	123.7
[O I]	6363.9	47	43.5
[N II]	6548.1	45	30.6
H_α	6562.8	314	295.8
[N II]	6583.4	139	77.1
[S II]	6716.4	72	(172)
[S II]	6730.8	109	(190)
[FeII]	7155	37	
[Ca II]	7291	29	
[OII]	7319		
[Ca II]	7324	10	
[O II]	7330		
[C I]	9849	$\lesssim$ 10	
[S II]	10318	11	
[S II]	10336	12	
[He I]	10830	133	

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(with respect to the surrounding medium). It is quite clear that these facts are of great importance for any theoretical interpretation of HH objects. Schwartz (1977) has recently measured radial velocities in individual condensations of HH 2. The results look rather complicated with certainly not all condensations showing negative radial velocities. It is not yet clear how results like these lead to average blue shifts for almost all observed HH objects.

Very recently the picture has become even more complex due to an important discovery by Herbig (1977) who studied the radial velocities in HH 32A (see Herbig's 1974 catalogue). He finds that the main nucleus has a velocity of about +8 km/s and a very broad line centered at about +280 ms/s and extending from +175 km/s to +400 km/s. This result clearly looks very different from the results stated above. The presently unanswered question is whether HH 32A forms just one single exception to the "rule" governing radial velocities of HH objects or whether we shall have to revise our ideas about the radial velocities in these objects completely.

There are only a few results available about the widths of the emission lines in HH objects. Böhm, Perry and Schwartz (1973) found Balmer line widths of the order of 1Å or smaller in HH 1. Strom, Grasdalen and Strom (1974) found somewhat larger line widths in some HH objects, especially in HH 11 and HH 29. Very recently Schwartz (1977) determined the line widths in a number of condensations of HH 2 obtaining values of the order of 1.5Å. In connection with attempts of theoretical interpretation the fact that the lines show only moderate broadening is of great importance (see below).

(b) Continuous Spectra

Continuous (or quasi continuous) radiation was already seen by Herbig (1951) in his very first spectroscopic study of HH objects. The original motive for continuum studies (cf. Böhm 1956) was of course the search for a central star. Though it is now known that there are no visible central stars (at least in the usual sense of the word) it is still important to study the continuum in order to obtain additional information about the physical conditions in HH objects. A recent attempt to measure the continuum in HH 1 and in condensation HH 2 H was made by Böhm, Schwartz and Siegmund (1974). The continuum is extremely faint and correspondingly the uncertainties in the results are rather large. However, there can be little

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doubt that a continuum (or quasicontinuum) is really present. This is also clearly shown in the observations by Schwartz (1976) with the Wampler scanner (see fig. 1 of his paper).

Some of the preliminary results for F_λ (corrected for reddening, Böhm 1975) are shown in fig. 1. One immediately realizes that this is not a continuum of a late type star (as had been suspected 20 years ago). In fact, it is not entirely clear whether we see a real continuum or a "quasicontinuum", i.e., a super-position of many faint emission lines. However, it has been shown that the observed apparent continuum cannot be due to forbidden and permitted Fe II lines (Böhm, Schwartz and Siegmund 1974). On the other hand, the large majority of faint resolved lines consists of [Fe II] lines. This makes it somewhat improbable that the observed continuum is really composed of many unresolved faint lines. It can also be shown that the observed continuum is not a simple nebular continuum composed of Paschen, Balmer and two-photon continua since it is too strong for the theoretical predictions (Böhm et al. 1974).

4. Reddening and Interstellar Absorption

Since HH objects occur in heavily obscured regions only (see Herbig 1969) the determination of their reddening is of great importance. It can be done best using Miller's (1968) method which is based on a comparison of the infrared (10318/10336) and the blue (4068/4076) multiplets of [S II] which have the same upper levels and therefore should have a fixed intensity ratio. Observed deviations from this ratio are an indication of reddening. This method is very well suited for HH objects since they have unusually strong blue and infrared [S II] lines. Miller's method also has the great advantage that it uses a very long "baseline" in wavelengths to determine the reddening. So far this method has been applied only to the NW part of HH 1 and condensations HH 2 H and HH 2 G of HH 2. The measured values of E_{B-V} are 0.60 for HH 1, 0.24 for HH 2 H, and 0.3 or less for HH 2 G (Böhm, Schwartz and Siegmund 1974). We find these values unexpectedly low if we consider that all HH objects are in regions of high dust concentration. Some authors have suggested (Strom, Strom and Kinman 1974) that in the regions of star formation the properties of dust particles may be different from those usually described by Whitford's (1958) reddening law. In that case we may have high interstellar absorption though the reddening is not

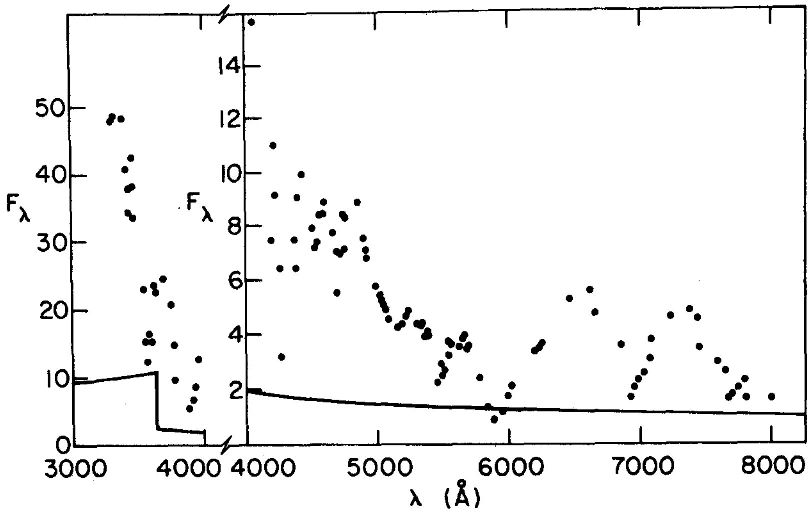

Fig. 1. Comparison of the observed continuum in HH 1 (filled circles) with the usual nebular continuum predicted for the average T_e and N_e in HH 1. (From data by Böhm et al. 1973).

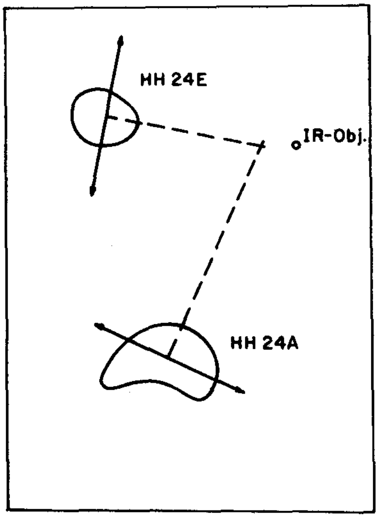

Fig. 2. The direction of linear optical polarisation in condensations HH 24 A and HH 24 E (indicated by arrows) in relation to the position of the nearby infrared source. This is a schematic drawing based on a photograph published by Strom, Strom and Kinman (1974).

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exceptionally high. It is of course also possible that a selection effect is present. The two brightest HH objects could just be those with exceptionally low reddening (and absorption). Further studies of the reddening of HH objects should be very helpful for a better theoretical understanding of these objects.

5. Polarization and Infrared Sources

One of the most interesting properties of some HH objects is the rather high degree of linear polarization of their optical radiation (Strom, Grasdalen and Strom 1974, Vrba, Strom and Strom 1975).

The most impressive case is certainly HH 24 in which the condensation A (Herbig's designation 1974) has a degree of linear polarization of 24% (Strom, Strom and Kinman 1974). The polarization angles for this and the condensation E (See Fig. 2) are such that Strom's reflection nebula hypothesis is very convincing in this case. At the other extreme we have the "classical" Herbig-Haro objects HH 1 and HH 2 in which the linear polarization is only 1.8 and 2.6% and the polarization angle agrees with that of the neighboring star V380 Ori (Schmidt and Vrba 1975) clearly indicating interstellar polarization only. Moreover, HH 1 and HH 2 also have a number of other properties which make it appear improbable that they are reflection nebulae, namely, the variation of radial velocities across the HH object (Böhm et al. 1973, Schwartz 1976) and the different line fluxes in different condensations of the same HH object. These condensations have distances from each other of only 10 light days (Böhm, Siegmund and Schwartz 1976).

So, it seems at present that we have different sets of observations which lead to contradictory conclusions. I can see only two possible ways out of this dilemma: Either Herbig-Haro objects do not really form a homogeneous group of objects, or we are misinterpreting the implications of at least one type of observation.

The first alternative has been discussed briefly by Schmidt and Vrba (1975) and Gyul'budadyan (1975). The second possibility has been mentioned by Haro (1976) who argues that in the dense regions considered very high degrees of <u>interstellar</u> polarization may also be possible and that such a high degree of polarization is not necessarily an indication of the operation of the reflection mechanisms.

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Both types of arguments are possible, but both do not look really attractive to me, and I prefer to admit that there is a real contradiction which we cannot yet resolve at the present time. The first way of reasoning would become much more convincing if we could spectroscopically or spectrophotometrically distinguish between two different classes of HH objects. It is not impossible that we shall be able to find such a criterion in the future since there is still a considerable number of HH objects for which no blue spectra are available.

The search for infrared sources originally was initiated for the same reasons as the studies of the visual continuum, namely to find a "central star". This type of investigation was put on a new basis by Strom and his collaborators (cf. Strom, Strom and Grasdalen, 1974) by searching for infrared objects outside the HH object. These IR objects are assumed to be extremely young, heavily reddened T Tauri like stars which can illuminate the Herbig-Haro reflection nebula. The results shown in fig. 2 illustrate this type of situation for the case of HH 24. Strom and his collaborators did not find IR sources <u>within</u> HH objects.

More recently, Schmidt and Vrba (1975) have found that HH 1 and HH 2 themselves are IR sources and have K magnitudes of 12.30 (HH 1) 12.62 (HH 2). These authors find that the IR radiation of these objects can be attributed to free-free transitions. However, in order to do this they have to use a considerably larger filling factor (namely 7×10^{-2}) than has been determined from the emission lines (these gave 1.3×10^{-3} for HH 1 and 1.5×10^{-3} for HH 2 H). This obviously means that it is still possible that a "real" infrared source (in contradistinction to the nebular free-free emission) may be responsible for the IR radiation in HH 1 and HH 2. The large (K-L) color index in HH 2 (~ 2.2) also points in this direction.

6. Quantitative Interpretation of the Spectra

An interpretation of the observed emission line spectra has been given on two different levels of sophistication:

(a) Homogeneous and Two-Component Models

From the statistical equilibrium equations for a homogeneous medium in which the excitation is due only to electron collisions we can determine the ratio of any two lines (usually forbidden lines)

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as a function of Te and Ne. Inverting this relation one finds (Seaton 1954) a relation $N_e = f$ (Te) for every observed (fixed) flux ratio of two forbidden lines. In a T_e- N_e diagram the "crossing region" of many such curves then determines the values of T_e and N_e for the object under consideration. If, in an application of this procedure the "crossing region" is very well defined, we may consider this as a justification of the assumptions made and also as an indication of the internal consistency of the systems of transition probabilities and collision strengths used. Typical results for the NW part of HH 1 and for condensation H of HH 2 are given in fig. 3. Studies of this type also seem to show that from 1955 to 1973 T_e and N_e in HH 1 have increased from $T_e \sim 7500K$: $N_e \sim 1.3 \times 10^4$ cm^{-3} to $T_e \sim 10{,}000K$; $N_e \sim 3.2 \times 10^4$ cm^{-3}. However, it is difficult to interpret this last result correctly since in 1955 the brightest part of HH 1 was the SE part (and the spectra taken then are strongly influenced by this part) whereas in 1973 (and now) the NW part is the brightest (Herbig 1973).

The diagrams very clearly show indications of density inhomogeneities. While the curves for most of the line ratios go through a single crossing region the [S II] 6731/6717 ratio obviously indicates a lower density (Böhm et al. 1973). When the [O II] 3726/29 doublet is resolved it shows an even lower density than the [S II] lines (Böhm et al. 1973).

These facts plus the absolute line fluxes (see below) can be "explained" quantitatively by introducing a "2-component model" in which the low density component with $N_e \sim 10^3$ cm^{-3} covers almost the whole volume whereas a high density component with $N_e \sim 3 - 6 \times 10^4$ cm^{-3} (depending on the condensation) fills only a fraction of the order of 10^{-3} of the total volume. Obviously the density in the low density component is the same as in the immediate surroundings (see Böhm, Perry and Schwartz 1973) of the HH object.

If absolute line fluxes can be determined (this has been done, e.g., for HH 1, HH 2, HH 46, HH 47, see Böhm et al. 1976, Schwartz 1976, Dopita 1977) a comparison of the square of the electron density determined from the emission measure to the square of the electron density found from forbidden line ratios permits us to determine filling factors. These always turn out to be very small even if we apply the procedure only to a single condensation (leaving out the

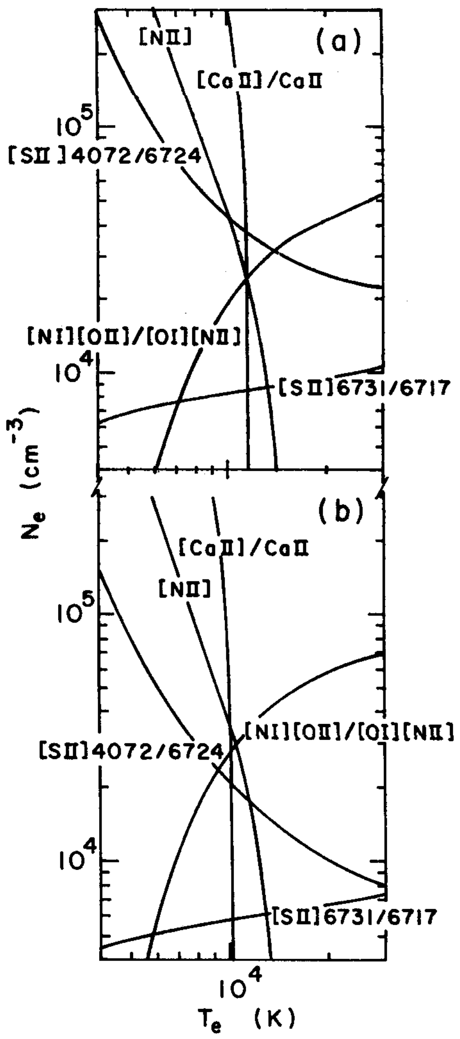

Fig. 3. T_e - N_e diagram for HH 2 H (a) and HH 1 (b). Reproduced from the Ap. J. 203, 399, 1976, published by the University of Chicago Press and the American Astronomical Society.

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low density regions between the condensations).

Thus, we are lead to the following geometrical picture of HH objects (see fig. 4). Most of the emission line formation in HH objects occurs in regions with $N_e \sim 3 - 6 \times 10^4$ cm^{-3}. However, these high density regions cover only a very small fraction of the total volume of HH objects. In the first place, the high density regions seem to occur only in the condensations of the HH object. In the regions between the condensations we only have "low density" material with $N_e \lesssim 10^3$ cm^{-3}.

Secondly, even within the observed condensations only 0.1 - 1.0% of the volume is filled by high density matter whereas the residual volume contains again matter of $N_e \sim 10^3$ cm^{-3}. (Böhm, Siegmund and Schwartz, 1976). A schematic description of the situation is given in figure 4. Because of this situation the line emitting regions of a single condensation in an HH object contains a mass of only 1-10 earth masses. However, one has to remember that only regions with (say) $N_e < 10^6$ cm^{-3} can be visible in the observed forbidden lines. Therefore it is not clear yet whether there are also undetected regions of higher density and whether the total mass could be substantially changed by the presence of such regions.

The observations also permit an empirical determination of the degree of ionization (Osterbrock 1958, Haro and Minkowski 1960, Böhm, Siegmund and Schwartz 1976). It turns out that in the two cases about which we have the most information, 46% (in HH 1) and 34% (in HH 2 H) of the total oxygen exist in neutral form. It is obvious that also with respect to the degree of ionization HH objects are essentially different from all other gaseous nebulae.

b) The Shock Wave Interpretation

The heuristic interpretation given above permits a determination of N_e, T_e, of filling factors and the average ionization, but it does not tell us where the energy for maintaining the degree of ionization and the electron temperature comes from. This has been an enigma for a long time. Though we still have not identified the ultimate source of the energy, we now understand a lot more about the mechanisms for ionization and maintaining the electron temperature. It was recognized very early that stellar radiation could hardly be the source for the ionization energy (Böhm 1956, Osterbrock 1958, Haro

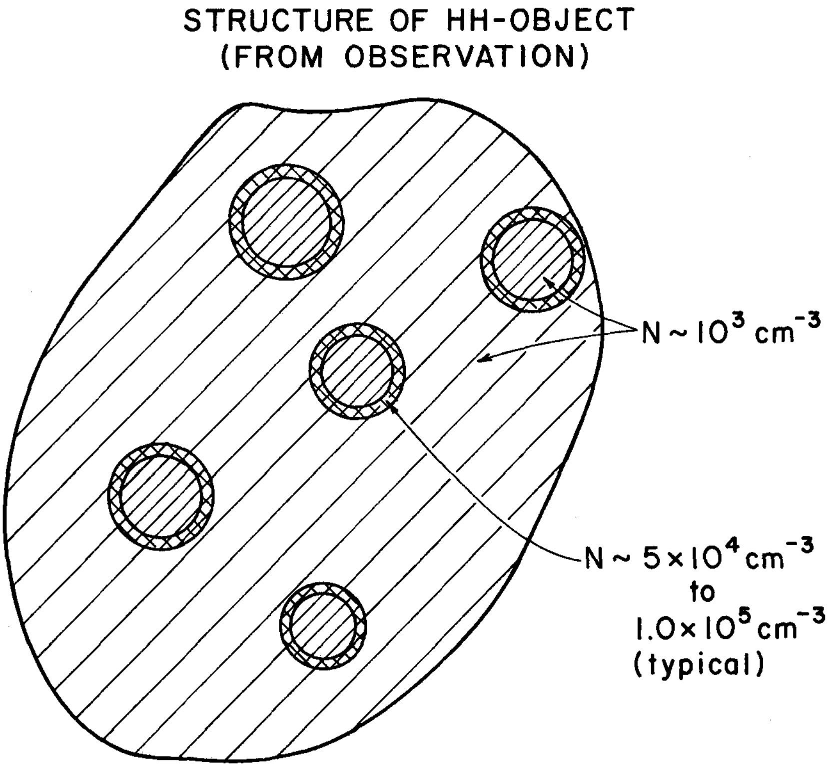

Fig. 4. Schematic picture of the structure of an HH object as derived from spectrophotometric studies in combination with direct photographs.

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and Minkowski 1960). Osterbrock (1958) emphasized especially that uv stellar radiation could not cause any conditions in which 50% of, e.g., O and H would be neutral in the line emitting regions. Other suggestions for the origin of ionization include the effects of a stream of fast protons (of about 100 kev, see Magnan and Schatzman 1965, Gyul'budagyan 1975) and ionization due to transition radiation (Gurzadyan 1974, 1975). We should note that if the ionization were due to moderately fast protons the Balmer lines should show extended wings due to the effects of charge transfer collisions (cf. Omholt 1971, Böhm, Perry and Schwartz 1973). So far such wings have not been seen.

Both of the above hypotheses require somewhat unusual physical conditions (e.g., a density of 200 electrons cm^{-3} with an energy of 1.5 Mev each in the transition radiation case). Moreover, in both cases no detailed theoretical predictions of the observed peculiarities of the typical HH emission line spectrum could yet be made.

It seems to us that at present the shock wave interpretation of the spectrum formation is the most promising one. The comparison with spectra of supernova remnants (see above) already points in this direction. The rough agreement of these two types of spectra is really somewhat surprising at first sight, since the shock waves in an HH object seem to move into an ambient medium with $N_e \sim 10^3$ cm^{-3} whereas the supernova remnant probably moves into an ambient gas with $N_e \sim 0.1$ -1 cm^{-3}. We know that the ambient density is one of the fundamental parameters determining the properties of a shock wave. (cf. Cox 1972a, 1972b).

Very recently detailed theoretical predictions of theoretical emission line spectra for shock waves under "Herbig-Haro conditions" have been made by Raymond (1977). He has calculated the visual as well as the uv and infrared spectrum for three models which may be appropriate for comparison with HH objects. (The models have a shock velocity of 60-70.7 kms^{-1}, an ambient electron density of 300-350 cm^{-3} and a magnetic field of 10^{-7} G). The results are shown in Table 2 in which the results for three different models are compared to our observational results for HH 1, HH 2 H, and HH 2 G. The overall agreement is rather reasonable though we have not yet reached the point at which there is a detailed agreement between the observational results for one condensation and the theoretical results for one corresponding model. However, apart from somewhat minor discrepancies which probably can be eliminated by choosing somewhat different model parameters there are also some more serious disagreements. For some lines, all the observations lie outside the range of the predictions of all three models. This is true for [O I] 6300 and for the infrared [Ca II] line 7291A. In the second case the discrepancy will probably disappear if the newer collisional cross-sections are used (as was done by Böhm et al. 1976, who could explain the Ca II K/ [Ca II] 7291 ratio at least for a constant T_e - constant N_e region). However, the fact that the observed [O I] 6300 line is much stronger than predicted poses a real problem. Since the observed line is very strong and has been measured independently by several observers the discrepancy certainly cannot be attributed to errors of measurement. Nevertheless, this discrepancy cannot be used as an argument against the shock wave theory since it has been found (Danziger and Dennefeld 1974) that several old supernova remnants in the Large Magellanic Cloud also show too strong [O I] lines in comparison to the theoretical predictions. Moreover, as emphasized above, in spite of a few remaining discrepancies, the agreement of the observations is so much better for the shock wave theory than for any other hypothesis that we strongly feel that it must be basically correct. (See also Schwartz 1975, Münch 1977, Dopita 1977). Once we accept this position, the next two questions are: (1) Can other properties (i.e., other than the spectrum) of HH object also be explained by the shock wave model? (2) Where do the shocks come from and what is their connection with early stellar evolution or star formation?

(c) Further Developments of the Shock Wave Theory

The first of the above questions leads to some difficulties because it is not obvious which properties of HH objects should be explained and which should be considered as accidental. For instance, looking at objects like HH 1, HH 2 and some similar objects one gets the impression that the individual condensations all have a size described by radii between (say) 300 and 900 a.u. In fact, almost all HH objects in Herbig's catalogue (1974) show (very roughly) such a structure. However, some of the HH objects found by Strom and his collaborators (cf. Strom, Grasdalen and Strom 1974) and by Schwartz (1977) are considerably larger and do not show such a condensation structure. In a similar way it is not yet clear whether the brightness changes which occur on a time scale of the

Table 2.

Comparison of Observed Relative Line Fluxes in 3 Condensations (Böhm et al 1976) with Predictions from the Shock Wave Theory (Raymond 1977) *

		Observations			Models		
		HH 1	HH 2H	HH 2G	Z	AA	FF
[O II]	3727	186.1	199.7	237.7	460	1116	235
[Ne III]	3869	T2.2	9.4	24.3	-	5.62	.47
Ca II	3934	12.0	11.8	-	12.3	13.6	9.57
[S II]	4073	66.8	41.5	50.3	13.8	27.5	8.70
[Mg I]	4571	9.9	11.9	-	-	12.0	8.00
[Fe III]	4658	27.8	11.0	-	6.5	52.5	-
$H\beta$		100	100	100	100	100	100
[O III]	5007	39.4	88.3	53.7	34.0	129	33.4
[N I]	5200	4.5	8.4	-	3.34	2.29	1.52
[N II]	5755	3	5.1	-	4.16	9.65	2.49
He I	5876	7.2	-	-	5.43	9.66	5.40
[O I]	6300	115.3	112.3	-	48.3	31.7	43.5
$H\alpha$	6563	265.8	330.7	486.8	505.	312.	747.
[N II]	6583	114.2	170.8	35.8	168.	236.	131.
[S II]	6717	82.7	27.2	15.5	27.5	48.7	13.9
[S II]	6730	107.8	39.8	-	43.3	69.0	3.9
[Ca II]	7291	29.1	23.7	49.5	2.9	3.1	1.5
[O II]	7320						
[Ca II]	7324 }	9.9	46.5	13.9	37.9	97.0	22.7
[O II]	7330 }						
[C I]	9849	-	11.3	-	245	82.5	123.
[S II]	10330	22.2	13.7	-	7.3	15.2	4.71
He I	10830	133.2	147.4	458.6	152	257	164

*) Taken from J.C. Raymond thesis with permission of the author.

order of 10 years in HH 1 and HH 2 are really typical for all HH objects. So, it is not surprising that there is no agreement yet about whether sizes and timescales of condensations should be explained by a theory or whether they should be considered as purely accidental. In a recent paper I have taken the first point of view (Böhm 1977). Surprisingly, it turns out that if we consider the observed particle density of $\sim 10^3$ cm^{-3} outside the condensations as typical ambient density for a spherical shock wave and use (in rough agreement with the observational results) 50 km/s as a typical shock velocity then the observed lifetime, size and filling factors of condensations are reproduced by the theory of spherical shock waves. Specifically, we find a "typical lifetime" (during which the condensation emits a considerable amount of radiation in the visible part of the spectrum) of about 14 years. During this time the spherical shock wave increases its radius from ~ 600 to ~ 900 a.u. The observed fact that the typical kinetic energy within one condensation is of the same order of magnitude as the radiation emitted during its lifetime makes this hypothesis rather convincing. On the other hand, it does have the awkward feature that a spherical shockwave has to be generated in each condensation individually. An energy input of about 10^{42} ergs is required for each condensation.

A different approach has been suggested by Schwartz (1977). A stellar wind hits a high density cloudlet and a bow shock is created (a similar mechanism has been studied for supernova remnants by Sgro 1975, see also McKee and Cowie 1975). The cooling regions of the bow shock and the transmitted shock are then identified with the visible condensation.

This hypothesis has the advantage that it tries to connect the radiation of the HH condensation with a well-known phenomenon, namely the stellar wind. On the other hand, I consider it as a disadvantage that (at least at the present time) the theory has to consider the sizes and time scales of condensations as somewhat accidental (though it cannot be excluded that this may be correct). Both theories face a problem (which is also present for all other hypotheses suggested so far) because they require either some sort of central stars or at least an energy source for the stellar wind or the shock waves which so far has not been identified.

In this context it is worthwhile to consider a question which

https://doi.org/10.1017/S0252921100069141 Published online by Cambridge University Press

has often been asked. Could it not be possible that the source of the stellar wind or the shock wave is one of the young stars which are observed outside the HH object itself but in the same general region. If this were correct, then in the case of the three best studied HH objects HH 1, HH 2, HH 3 (see Herbig 1951) the only reasonable candidate seems to be the Ae star V380 Orionis, the central star of NGC 1999. It is obvious that a bright condensation in HH 2 (say HH 2 H) cannot obtain its observed visual luminosity of $\sim 10^{32}$ erg s^{-1} or more (cf. Böhm 1975) from a spherically symmetric stellar wind from V380 Ori. Assuming an angular distance between V380 Ori and HH 2 H of $\sim 250"$ (see Herbig 1951) and an angular radius of HH 2 H of $\sim 1"$ (Böhm, Siegmund and Schwartz 1976) we find that V380 Ori must have an energy output of at least 2.5×10^{38} erg s^{-1} corresponding to 0.6×10^5 $L_\odot$ in the form of a stellar wind alone. This seems to be definitely impossible. Consequently, we must continue to search for energy sources which are within the HH objects or at least very near to them.

Acknowledgements. I am grateful to Dr. G.H. Herbig for informing me about his observations of HH 32 A in advance of publication and to Dr. J.C. Raymond for the permission to reproduce Table 2 from his thesis.

This study has been supported by NSF grant AST 76-22262.

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D I S C U S S I O N of paper by BÖHM:

WILSON: What observational handles exist on the opacity due to dust and have you included effects of dust in your model calculations of relative line strengths (dust would prevent seeing the main part of the nebula). Dust opacity is suggested by the consistently negative radial velocities.

BÖHM: Though the extinction in front of the shock can be derived from the observed E_{B-V} we have no information yet about the possible importance of dust within the cooling region of the shock. Dust has not yet been taken into account in the calculation of the line spectrum.

APPENZELLER: Does the presence of the neutral atoms observed in the spectra of HH objects present any difficulties with the observed temperature ($\sim 10^4$ K) and the shock-front explanation of this phenomenon?

BÖHM: As has been emphasized in Raymond's thesis the interpretation of the [OI] lines leads to some difficulties in the shock wave theory. However, similar difficulties occur in the interpretation of the spectra of some supernova remnants. It is therefore believed that these problems are due to the physical approximations used in the calculations, and do not indicate a fundamental error in the shock wave hypothesis.

R.N. THOMAS: Could you give characteristic data for T_e, N_e and R for the condensation?

BÖHM: Raymond's calculations (Ph.D. Thesis, Univ. of Wisconsin, 1977) show that for shocks corresponding to HH conditions, the shock temperatures are between 6×10^4 K and 9×10^4 K. In the cooling regions (i.e., the regions of spectrum formation) the temperature is not too different from 10^4 K. The number density in front of the shock is 300 - 350 cm^{-3}. The density in the cooling regions is of course considerably higher. The characteristic thickness is of the order of a few astronomical units.

MATTEI: Do you find any evolutionary sequence between HH objects and T Tauri stars or do you treat them independently?

BÖHM: The work reported here aims at the direct interpretation of the observations and the determination of the physical conditions in HH objects. It has not yet given us direct information about the evolutionary significance of HH objects.

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An important connection between HH objects and T Tauri stars (apart from their spatial distribution) is, of course, shown by the fact that Burnham's nebula (surrounding T Tauri) has the properties of a HH object.

HABING: As a comment on the high-velocities observed in Herbig Haro objects I would like to remind you of the high velocities found in those H_2O masers that are associated with regions of star formation.[2] These velocities may in a few cases run up to 200 km s^{-1}.

BÖHM: This analogy may be very important. It has also been mentioned by Lo, Morris, Moran and Haschik (Ap. J. 204, L21, 1976).

FRIEDJUNG: Have you attempted to determine the reddening using the [FeII] lines? (Method of Viotti and Pagel). This would check the results from [SII].

BÖHM: This has not been done. Miller's method works well since the wavelengths' base line is very long. The [FeII] lines are rather faint, and the photometry of these lines is not too good in HH objects.

KOPAL: What is the energy source which keeps the shock-wave model running for 10 years (or 10^8 sec)?

BÖHM: A total energy of about $E \sim 10^{42}$ ergs is required per typical condensation. The source of this energy is still unknown.

DZIEMBOWSKI: Why do you prefer the expanding shock wave interpretation to the standing shock wave interpretation?

BÖHM: We did not see any simple way to explain the preferentially negative radial velocities (of $\sim$50 km/s) by standing shock waves.