HERBIG-HARO OBJECTS

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Abstract

After a brief introductory discussion of the statistics of known Herbig-Haro (HH) objects we present a survey of recent spectroscopic results in the ultraviolet, the optical and the near infrared range (the latter mostly in connection with H_2 observations). We emphasize the importance of the use of spatially resolved line profiles (position-velocity diagrams) in the optical range for the purpose of testing hydrodynamic models of HH objects. Such observations have now been supplemented by the measurement of spatially dependent intensity ratios for a large number of optical lines ~200 in HH 1) and of some ultraviolet lines (including fluorescent H_2 lines) which are very useful for diagnostic purposes. The relevance and importance of spectroscopy and imaging in the infrared H_2 lines is discussed.

In the second part of the paper we review the present status of the interpretation of spatially resolved spectra and of monochromatic images by hydrodynamic models. We emphasize the successes as well as the shortcomings of the bow shock interpretation of HH spectra and point out that there are a few cases (*e.g.*, HH 43) in which a "shocked" cloudlet model is more appropriate than the model of the working surface (plus bow shock) of a jet. We discuss the intriguing [Fe II] problem.

I. Introduction

In recent years our understanding of Herbig-Haro objects has increased rapidly. In the middle to late 70s it became completely clear that optical HH spectra are spectra of shock waves (Schwartz 1975; Böhm, Siegmund and Schwartz 1976; Dopita 1978a, b; Raymond 1979) and that they occur under a wider range of environmental conditions than was originally thought (Münch 1977). Guido Münch has contributed to both results in an important way. His discovery of an HH object in the Orion nebula was of special importance and was the first of a series of such discoveries in H II regions (see *e.g.*, Axon a. Taylor 1984). In the early to mid eighties the idea that HH objects are tracers of highly collimated bipolar jet-like flows from young stars or even protostars became more or less generally accepted. (See *e.g.*, Mundt and Fried 1983; Strom, Strom and Stocke 1983; Mundt *et al.* 1984; Mundt 1985; Strom *et al.* 1986.) It also became clear that often (but not always) the brightest HH objects occur near th end of jet and might be identified with the "working surface" (either the bow shock or the jet-shock, see *e.g.*, Blondin, Königl. Fryxell 1989).

We feel that one of the most important discoveries which led to the general acceptance of these ideas were the proper motion studies by Herbig and Jones (see *e.g.*, 1981, 1983) which showed convincingly that the velocity vectors in the jet flows point indeed radially away from the central star.

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At present we have therefore a more or less accepted scenario which gives a very qualitative explanation of Herbig-Haro objects, their relation to bipolar jets and to the circumstellar matter of young stars in general. There remain a large number of unanswered questions, of which we mention three:

1. By which physical mechanisms are the highly collimated jets generated?
2. What is the detailed radiation-hydrodynamics of the HH objects. How can it explain the important observational facts including the spatial variation of line intensities in the UV, optical range and the infrared, the radial velocity field and the radial velocity dispersion as well as the different proper motions of the individual clumps of a single HH object. There is certainly some discrepancy between the optimism which comes from the fact that we do understand Herbig-Haro objects in a very crude way and the difficulties which one encounters if one wants to explain spatially resolved spectra even in an approximate way.
3. Is the standard scenario with HH objects being due to shocks at the working surface of the jet or to internal jet shocks really applicable to all HH objects? Since the detection of an HH spectrum really indicates only the presence of a shock we would not necessarily expect that all HH objects must be explained by the standard scenario. Recent detailed studies of some HH objects more or less force us to accept a different explanation in a few cases (*e.g.*, in HH 43 and HH 24, see Schwartz, Dopita and Cohen 1985; Böhm and Solf 1989; Solf 1987).

In this review I shall concentrate on the observations relevant to points 2 and 3 and their interpretation. Certainly point 1 is the most fundamental one. It is, however, treated in Tenorio-Tagle's (1989) and in Cantó's (1989) paper (see also Dyson 1987). The coverage of our review will be more restricted than that of Mundt (1987) who also included a discussion of jets and their central stars.

II. The Number of Known Herbig-Haro Objects

This paper will be mostly concerned with the study of physical processes and the interpretation of spectra applied to a few selected interesting HH objects.

In order to remind ourselves that HH objects are much more common than indicated by the few objects mentioned below it seems appropriate to state at least very briefly how many HH objects are known. This is, of course, not a very precisely defined question since it is a matter of definition whether the individual condensations in a small compact HH complex is counted as a single object or whether the whole complex should be counted as one HH object.

Usually HH objects are assumed to occur only in regions of recent star formation and we follow this assumption. More general definitions have also occasionally been used (*e.g.*, Cohen 1987).

As is well known Herbig (1974) published the original and extremely useful "standard" catalog of HH objects. It contains 77 objects if we consider every individual condensation listed (*e.g.*, HH 24A, B, C, D) as a separate object. In the meantime many new HH objects have been discovered through the efforts of Graham, Hartigan, Meaburn, Mundt, Reipurth, Schwartz,

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the Stroms and many others. There is now a new, very useful catalog of HH objects by von Hippel, Burnell and Williams (1988) which lists 184 HH objects (again counting individual condensations as separate objects). The authors have restricted themselves to objects for which their identification as HH objects is not in doubt.

One might have some doubt about considering individual condensations as individual objects. If they really owe their existence to hydrodynamic instabilities in a bow shock (as considered by Raga and Böhm 1987 and Raga *et al.* 1988) then they are, of course, short-lived transient features only (in agreement with some observations (see Herbig 1969)). But this is really a minor point and a matter of opinion.

III. Spectroscopy and its Interpretation

Optical: In view of the fact that spectroscopic studies of HH objects have been carried out already in the 1950s (Herbig 1951; Böhm 1956; Osterbrock 1958) it would seem surprising that it should be possible to get still important new insights from optical spectroscopy. But this is definitely the case. The progress has been based mostly on a) high spatial resolution spectroscopy (Hartmann and Raymond 1984; Böhm and Solf 1985; Schwartz, Dopita and Cohen 1985; Solf, Böhm and Raga 1986; Solf 1987; Solf and Böhm 1987), b) high spectral resolution obtained by using echelle or coude spectrographs and c) highly improved spectrophotometry using CCDs and other modern detectors. Typically spectral resolutions of up to ~0.3 Å (corresponding to ~15 $\mathrm{km\,s^{-1}}$ velocity at Hα) and spatial resolutions of 1″ (seconds of arc) have been achieved for a number of brighter emission lines in the moderately bright HH objects. The amount of information contained in these spatially resolved line profiles ("position-velocity diagrams") is considerable and can be used for rather sensitive tests of theoretical models. The position-velocity diagrams as well as spatially integrated line profiles have played an especially large role in the test of bow shock model of HH objects. (See *e.g.*, Choe, Böhm and Solf 1985; Raga and Böhm 1985, 1986, 1987; Hartigan, Raymond and Hartmann 1987; Raga *et al.* 1988; Solf, Böhm and Raga 1986.)

Spatially resolved high resolution spectroscopy (with 15-20 $\mathrm{km\,s^{-1}}$ resolution) is available 12 of the brighter HH objects (HH 1, HH 2, HH 3, HH 7, HH 8, HH 10, HH 11, HH 12, HH 24, HH 32, HH 34, HH 43, HH 47). Of these HH 1, HH 2, HH 24, HH 32 and HH 34 have been studied in specially great detail and it is well known that specially for HH 1, HH 32, and HH 34 relatively detailed bow shock models have been developed which reproduce position-velocity diagrams fairly well whereas the position-velocity diagrams of HH 7-HH 11 so far have not permitted any simple hydrodynamic explanation.

More recently spatially resolved echellette spectra of high spatial but moderate (1-2 Å) spectral resolution have supplied us with a wealth of new information (Solf, Böhm and Raga 1988; Böhm and Solf 1989). They permit the simultaneous coverage of the wavelength range $3720 \lesssim \lambda \lesssim 10830$ Å and have lead to the discovery of many new lines and the measurement of the spatial variation of intensities and radial velocities of these lines. The measurement of the spatial distribution permits us to decide immediately whether a line is formed in the HH object or in its environment. Newly discovered lines include extremely low ionization like the NaD lines as well as quite high ionization lines like the A IV lines. Since the instrument is very sensitive the spatial variation of quite faint lines can be studied. This includes the "auroral" lines of [O I], [C I], [N II], [O II], [S II], [O III] permitting us to determine the spatial variation of the electron temperature in the line forming regions of these ions from the spatial variation of the ratio of "auroral" to "nebular" lines. A comparison of the electron temperatures for the line-forming regions for different ionization stages gives us a new and very direct proof of the presence of shock waves. It varies (*e.g.*, in HH 1) monotonically from $T_e \sim 1.0 \times 10^4$ K for the [C I] regions to $\sim 4.5 \times 10^4$ K in the [O III] regions. The information about the spatial variation of up to 200 lines in a single object permits very sensitive tests of the hydrodynamics of an HH object.

Let me arbitrarily select three interesting problems which have resulted from recent spectroscopy studies.

1. If we interpret the spectra in terms of bow shock models (which is certainly appropriate in many cases, see above) we find that there are a few objects for which the jet model (or a bullet model) is not acceptable. HH 43 is the best example it as three condensations A, B and C. The radial velocity is relatively large and negative (50 to -60 km s^{-1}) in most places. Only "in front" of each condensation does the velocity go to values of ~ -10 to -20 km s^{-1}. This can be only understood if the flow (stellar wind) is brought to rest in front of the three obstacles HH 43A, B and C which is exactly the situation which is considered in the "shocked cloudlet model" (Schwartz 1978).

2. Studying the spatial variation of a larger number of line ratios in bow shock-like HH objects we find *e.g.*, in HH 1 excellent to good agreement in a fairly large number of line ratios including [O II] 3727/Hα, [O III] 5007/Hα, ([S II] 4069/76)/Hα, ([S III] 6716/31)/Hα, [N II] 6583/Hα, [S II] 9532/Hα, ([N I] 5198/5200)/Hα. There are other ratios (*e.g.*, [O I] 6300/63/Hα) for which the agreement is qualitative only. For a very few lines there is fairly strong disagreement between prediction and observation. These include the [A III] lines though the fairly similar [O III] and [S III] lines show agreement between observation and theory.

3. The sensitivity of the instrument permitted us to study a large number of [Fe II] lines in several HH objects. At present there is not yet enough information about collision strength available in order to carry out a convincing abundance analysis. Nevertheless, the following quite intriguing result can be easily obtained. The average intensity ratio of the [Fe II] lines to, say, Hβ is drastically different for different objects It varies about a factor 10 in the objects observed so far. However, contrary to our naive expectation the [Fe II]/Hβ line ratio is not correlated with the excitation of the HH object (*i.e.*, low excitation objects do not on the average show [Fe I]/Hβ ratios different from those of high excitation objects). This indicates that these average line ratios are neither a direct consequence of the presently observed excitation or ionization nor they are a consequence of the present grain destruction which should be related by the presently observed shock strength. Surprisingly the [Fe II]/Hβ ratio seems to be constant for objects which belong to the same HH complex. For instance, the three objects HH 43A, B and C which lie very close together in space (within $\sim 30''$) all show the same unusually low [Fe II]/Hβ ratio although HH 43A is a high excitation object (comparable to HH 1) and HH 43B and C are definitely low excitation objects

Ultraviolet: The earlier I.U.E. observations of HH objects have been discussed in preceding review papers, *e.g.*, Schwartz 1983c, 1985; Böhm 1983. One of the basic "old" I.U.E. results was the dramatic difference between "high excitation objects" (represented by HH 1, HH 2, HH 32, see Ortolani and d'Odorico 1980; Böhm, Böhm-Vitense and Brugel 1981; Brugel, Shull and Seab 1982; Böhm-Vitense *et al.* 1982; Böhm and Böhm-Vitense 1984) and "low excitation objects" (represented by HH 43 and HH 47, see Schwartz 1983a, b). High excitation objects show C IV 1550 and C III] 1909 as the strongest lines in the IUE short wavelength range (1250 Å $\lesssim \lambda \lesssim$ 1950 Å) whereas low excitation HH objects show almost only fluorescent H_2 lines (probably pumped by the very strong Lα emission of the shock. The fact that no intermediate objects are seen is impressive but the HH object sample accessible with IUE is still too small to draw convincing conclusions in this respect.

During the last few years very long (2-shift) exposures of I.U.E. spectra of HH objects have been obtained and (together with archival data) been used mostly in connection with two problems:

1. Attempts to determine the spatial distribution of continuum and line emission also in the ultraviolet and a comparison of the results to analogous optical data (see above).
2. A more detailed study of the wavelength dependence of the ultraviolet continuum and a test of the hypothesis that the ultraviolet continuum as well as the optical continuum is due to collisionally enhanced two-photon emission. (Dopita, Binette and Schwartz 1982; Brugel, Shull and Seab 1982.)

With regard to point 1, special precautions are necessary. The point-spread function of I.U.E. and the variation of the sensitivity (see Clarke and Moos 1981) have, of course, to be taken into account. The results of 1 agree to a large extent at least qualitatively with expectations (Böhm *et al.* 1987; Lee *et al.* 1988). Emission regions of C IV 1550 and C III] 1909 are typically small and comparable to [O III] emission regions. Surprisingly the emission regions of Mg II 2800 and C II] 2326 are also relatively small. The continuum emission region in the short wavelength range (1250 Å $\lesssim \lambda \lesssim$ 1950 Å) of IUE is (spatially) considerably more extended than the emission regions of IUE long wavelength and of the optical range (which agree with each other). We consider this as an additional evidence that in the SW region of IUE a second continuum emission process is important in addition to the collisionally enhanced two-photon emission which essentially determines the continuum in the optical and long-wavelength IUE ranges.

The measurements described under 2 showed that the observed wavelength dependence in the SW range of IUE is not compatible with a pure two-photon continuum (Figure 1). Our tentative conclusion was that a superposition of a collisionally enhanced two-photon continuum and a fluorescent H_2 continuum (see Dalgarno, Herzberg and Stephens 1970) would fit the observations much better.

We are now also studying the spatial emission distribution of the fluorescent H_2 lines in the low excitation objects HH 43 and HH 47. Interestingly, we find that, in both HH 43 and HH 47, the lines are formed in considerably smaller regions than the continuum.

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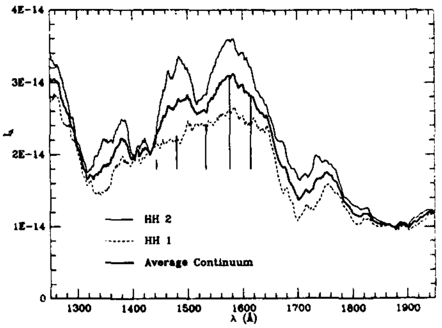

Figure 1. The observed continuum of HH1 and HH2 in the short wavelength range of IUE. The length of the vertical lines in the range 1440 Å $\lesssim \lambda \lesssim$ 1660 Å give a crude description of the expected wavelength dependence of the fluorescent H_2 continuum (from Böhm *et al.* 1987).

Near Infrared H_2 Emission. The emission of HH objects in the infrared quadrupole H_2 lines is of great interest and so far has supplied us with interesting but only partially understood information. Schwartz, Cohen and Williams (1987) have detected H_2 IR emission in many HH objects most of which are low excitation objects.

Imaging of HH objects in the light of H_2 quadrupole lines is of great interest. Results by Zealey *et al.* (1986) showed already the very close association between H_2 and optically emitting regions in HH 32. High resolution imaging of HH 43 in the 0-1 S(1) line of H_2 (2.12 μ) by Schwartz *et al.* (1988) shows a very strong correlation between the H_2 and the optical emission of HH 43.

Of very great interest in this context is the H_2 emission of the chain of HH objects HH 7-HH 11 which was observed first in the H_2 lines by Zealey, Williams and Sandell (1984) and Lightfoot and Glencross (1986). Recently Zinnecker *et al.* (1989) have studied the line profiles of the 2.12 μ line in these objects and have found suprising similarities with optical lines in the following sense. The optical line profiles are known (with a velocity resolution of 15 - 20 $\mathrm{km\,s^{-1}}$) from coude spectra (Solf and Böhm 1987). They show somewhat complex line profiles which differ from object to object. The H_2 line profile looks (at least qualitatively) similar to the optical profiles for each individual object. However, quantitatively the lines are consistently somewhat narrower and less blue-shifted than the optical lines. The authors suggest entrainment of molecular gas into the jet forming HH 7-HH 11 as the probable (qualitative) explanation of observed line profiles. The explanation is complicated by the fact that HCO^+ line profiles observed by Rudolph and Welch (1988) show clumps of high density matter ($N \sim 2 \cdot 10^5\ \mathrm{cm}^{-3}$ or larger) just "downstream" of HH 10 and HH 8. Rudolph and Welch (1988) argue that this favors the "shocked-cloudlet" model (Schwartz 1978). However, the study of optical position-velocity diagrams (Solf and Böhm 1987) and line profiles (Hartigan, Raymond and Hartmann 1987) indicates that HH 7-HH 11 can be described neither by the shocked cloudlet nor by the bullet model. It is my definite impression that at least in the case of HH 7-HH 11 more theoretical insight is needed before we can have models which permit a synthesis of optical, IR (*i.e.*, H_2) and radio (*e.g.*, HCO^+) observations.

It would be useful to make a comparison of the spatial distribution of the IR H_2 emission and the fluorescent H_2 emission in the UV. We are carrying out such a study for HH 43 using the IR data by Schwartz *et al.* (1988) and new two-shift I.U.E. spectra which we have obtained recently.

IV. The Interpretation of HH Spectra in Terms of Hydrodynamic Models: Success and Unsolved Problems

In the preceding chapters we have discussed ultraviolet, optical and infrared spectroscopy of HH objects and its interpretation, using some illustrative examples.

How successful are hydrodynamical models in general in explaining HH spectra? Before we can answer this we have to state more precisely what we want to explain. Our aims are ambitious. We want to predict

a. the total line fluxes integrated over the whole object (see *e.g.*, Hartmann and Raymond 1984)

b. high resolution line profiles (Hartigan, Raymond and Hartmann 1987)

c. position-velocity-diagrams (see *e.g.*, Choe, Böhm and Solf 1985; Böhm and Solf 1985; Raga and Böhm 1985, 1986; Solf, Böhm and Raga 1986)

d. the spatial variation of the intensity ratios of many lines (Solf and Böhm 1988; Böhm and Solf 1989)

e. the proper motion of "clumps" (condensations) of HH objects (see *e.g.*, Herbig and Jones 1981, 1983; Schwartz, Jones and Sirk 1984; Jones and Walker 1985) In practice position-velocity diagrams have been determined for only a small number of lines because otherwise the required observing time becomes very large. It is much easier to study the spatial variation of the total intensity of a given line (rather than of the line profile).

In a number of objects either a part or all of the above listed observations have been explained successfully by bow shock models. This is especially true for HH 1, HH 32, HH 34, HH 43, HH 47 and (to a lesser extent) HH 2 (see *e.g.*, Choe, Böhm and Solf 1985; Raga and Böhm 1986; Reipurth *et al.* 1986; Solf, Böhm and Raga 1986; Hartigan, Raymond and Hartmann 1987; Raymond, Hartigan and Hartmann 1988; Raga *et al.* 1988). If we restrict ourselves to the interpretation of (spatially integrated) line profiles and to line flux ratios. the bow shock models have been tested and shown to be applicable to many more HH objects (Hartigan, Raymond and Hartmann 1987). For the interpretation of flux ratios, integrated line profiles, and position-velocity diagrams simplified stationary bow shock models have usually and successfully been used. In these the geometrical shape of the bow shock is determined in advanced and then every small piece of the bow shock is approximated by a plane (usually oblique) shock for whose recombination region the line emission can be studied in detail. This approach was first used by Hartmann and Raymond (1984) for the study of flux ratios and by Choe. Böhm and Solf (1985) and by Raga (1985) and Raga and Böhm (1985) for the study of high resolution position velocity diagrams.

This simplified approach cannot be used for the study of the formation of individual condensations (clumps) of a HH object and of their proper motions. Raga and Böhm (1987) therefore have carried out numerical simulation of 2-dimensional time-dependent bow shocks.

While adiabatic flows approach (after some time) the known stationary solution the non-adiabatic (radiative) flows show at high Mach number thermal instabilities somewhat similar to those discussed by Falle (1981) and Innes (1985) for the one dimensional case. Raga *et al.* (1988) found that calculations of this type for a bow shock of 185 $km\,s^{-1}$ stagnation velocity predict a pattern of condensations, a distribution of proper motions (of the individual condensations), monochromatic Hα and [O III] images and position-velocity diagrams of Hα which are all in (at least qualitative) agreement with the observations (Figure 2). This is probably the most detailed and critical test of the bow shock theory for an HH object so far. One has, of course, to keep in mind that the computations are restricted to two space dimensions (axial symmetry) while the real hydrodynamics of the object is three dimensional. Other very critical tests of the bow shock theory have been done for HH 32 (Solf, Böhm and Raga 1986; Hartigan, Mundt and Stocke 1986). In this case, the rather complex position velocity diagrams could be explained. Also the surprising "double layer" effect (the fact that the "low" velocity component of the line has its spatial maximum always $\sim 0.''5 - 0.''7$ farther away from the central star than the spatial maximum of the high velocity component) has been explained in terms of bow shock models (Raga, Böhm and Solf 1986).

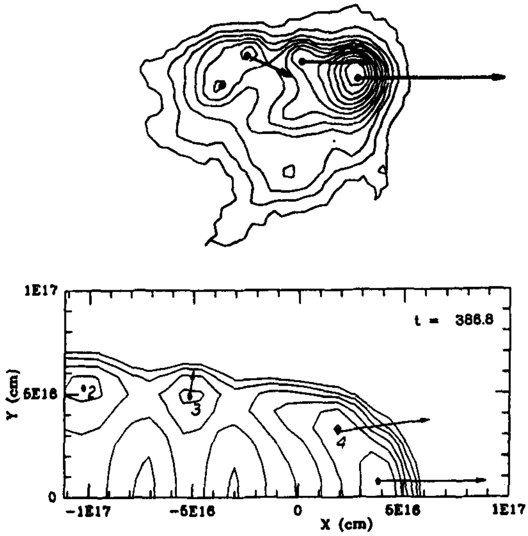

Figure 2. Comparison of observational data for HH1 (upper part) and theoretical predictions (lower part for a time-dependent non-adiabatic bow shock model (V_s = 185 $km\,s^{-1}$). The contour lines show the spatial intensity distribution (indicating the condensation structure of the HH object), the arrows show the proper motions of the individual condensations. (The proper motions have been transformed to a system in which the condensation with the smallest motion has a velocity of zero.) The theoretical model is axisymmetric (only half of it is shown). Because of this and because of the time dependence the theory and the observations are not fully comparable. It is, however, impressive that the theory reproduces the observations qualitatively well. Based on data from Raga *et al.* (1988).

A more sophisticated approach to the interpretation of the observations and specifically of monochromatic imaging has recently been used by Raga (1988) and in the work of Blondin, Königl and Fryxell (1989), in which the hydrodynamics of the heads of radiative jets including the outer bow shock has been studied. In principle, this is, of course, a more convincing approach than the above mentioned studies of pure bow shocks. It shows that the observed HH emission may be due either to the bow shock or the jet shock or both. At present such calculations still have to make drastic approximations about the details of the formation of the emitted spectrum (as is the case also for the time dependent two dimensional simulations of bow shocks). Consequently the calculations are not yet well suited for a prediction of flux ratios or of position velocity diagrams in many different lines. For these one would at present still have to go back to the simplified stationary bow shock models described above.

There are objects which do not seem to be connected with working surfaces of jets. Let us quote a few examples. If the condensations in jets are internal shocks (see Binette, Raga and Cantó 1989) the clumps in the HH34 jet are a good example (Reipurth *et al.* 1986; Bührke, Mundt and Ray 1988; Raga and Mateo 1988). They often show very low excitation with [S II]/Hα ratios up to 10. Then there are objects (with HH 43A, B and C being the best examples) which definitely seem to be shocked cloudlets (Schwartz, Dopita and Cohen 1985; Böhm and Solf 1989). The strongest evidence for this comes from the mapping of the radial velocity field (see above). In this case bow shock models are still applicable, but the usual jet models are not.

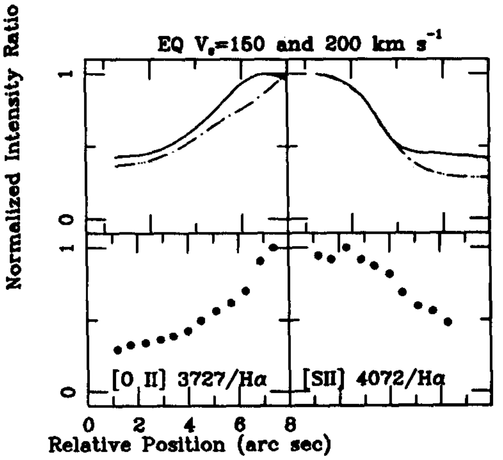

Figure 3. Comparison of the observed (lower part of figure) and predicted spatially dependent intensity ratios [O II] 3727/Hα, [S II] (4068 + 4076)/Hα The observations refer to HH 1, the theoretical predictions are made for bow shock models with V_s = 150 km s^{-1} (solid line) and V_s = 200 km s^{-1} (broken line). The bow shock axis lies in the plane of the sky. A comparison of theory and observations for many more line ratios will be presented and discussed in detail in a forthcoming paper by Noriega-Crespo, Böhm and Raga (1989).

Finally, there are objects like the HH 7-HH 11 chain of objects which (at least in our own opinion) so far have not been explained in a satisfactory way. It has been suggested that they are shocked cloudlets (Rudolph and Welch 1988) or a jet with entrainment of molecular matter (Zinnecker *et al.* 1989). Blondin, Königl and Fryxell (1989) have interpreted the HH 7 part as the working surface of a "light" jet in which the ratio of the cooling distance to the jet radius is small. All these suggestions explain certain aspects of the observations well but we feel that the explanation *e.g.*, of the detailed velocity field, the very abrupt transition in the velocity field from HH 11 to HH 10, the unusual position-velocity diagram of HH 11 have not yet been explained (see Solf and Böhm 1987).

Even in the cases in which most of the observations are compatible with bow shock models (*e.g.*, HH 1, HH 32, HH 34, HH 43 etc.) some intriguing problems remain. Recently many new data have been obtained for these and other objects (for instance, in the case of HH 1 the spatial emission distribution can now be studied in about 200 emission lines, see Solf, Böhm and Raga 1988). Taking HH 1 as an example we might ask: Do we continue to get good agreement with bow shock model predictions if we test many emission lines? We are presently trying to answer this question by using an approach analogous to that of Raga and Böhm (1986) but calculating spatially dependent line intensities (instead of profiles, see Figure 3) and doing this for many lines (Noriega-Crespo, Böhm and Raga 1989). The results which we have obtained so far are not as simple as we had expected and are in fact quite intriguing. In order to make the test as sensitive as possible we have studied the spatial dependence of the intensity ratio of the lines to $H\alpha$. The curves describing the spatial variation of this ratio differ drastically from emission line to emission line and it is improbable to get even the qualitatively correct behavior by accident. We find very good agreement between theoretical predictions and observations of the spatial intensity distribution of $H\alpha$ and the line intensity ratios of $H\alpha$ of to the [O III], [S III], [O II], [S II], and [N II] lines. It is especially impressive that the completely different variations of the [S II] 4068/76 $H\alpha$ and [S II] 6716/31/$H\alpha$ are both very well explained. Qualitative agreement of varying degrees between observation and theory is found for the ratios involving [O I], [N I] and (marginally) [C I]. It is interesting to note that there is qualitative disagreement in two cases namely [Ca II] 7291/$H\alpha$ and [A III] 7136/$H\alpha$. Because of the very low ionization energies of both Ca I and Ca II (6.1 and 11.9 eV) and the relatively high transition probability of the 7291 line (1.3 s^{-1}) this line tests probably different parts (namely low T, high g) of the shock recombination regions than all the other lines mentioned above. Therefore, it is at least possible that shock models with greater accuracy in the relatively cool parts of the recombination regions may lead to better agreement. The discrepancy for the [A III] 7136/$H\alpha$ ratio is considerably enigmatic because the ratios of the [O III] 5007 and [S III] 9532 lines to $H\alpha$ can be explained rather well. In principle observational material for the spatial emission distribution of $\sim$ 200 lines is available. The program which is used for the theoretical predictions (basically due to Alex Raga) permits the use of any (axially symmetric) bow shock like shape. We intend to find out whether some (not too unreasonable) modification of the bow shock shape would lead to even better agreement with observations. The result of such an attempt would (in combination with further hydrodynamic studies) be very helpful for finding reliable hydrodynamic models of HH objects.

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Discussion:

OSTERBROCK: The excellent agreement between the observed and predicted spectra is highly convincing that the general model is correct. Concerning the [FeII]/Hβ ratio problem, can you say whether the ratios of the individual [FeII] lines to one another are the same in various objects, or if they differ?.

BÖHM: The [FeII] line ratios agree qualitatively in different objects (in the sense that e.g., [FeII]λ7155 is always the strongest [FeII] line) but not quantitatively.

MÜNCH: Because, to my knowledge, no calculation of collisional excitation cross sections for the metastable levels of C^0 has ever been made, may I ask what kind of estimates have you used to determine T_e from the [CI] lines?

BÖHM: I am not sure whether your statement applies also to the long-lying metastable levels which are the upper levels of the [CI] λ9849, λ9823 and λ8727 lines. In any case Aller in his 1984 book on gaseous nebulae quotes collision strengths for these lines. In the moment I do not remember on which original work these results are based but I shall check this.

PECKER: From the analysis of line intensity variations, what can you say about the variations of N_e is the variations of T_e? which effect dominates?

BÖHM: In the "auroral" to "nebular" line ratios the T_e variation is of course the most important one. The spatial dependence of many line ratios is also strongly influenced by variations in the ionization equilibrium and by the question whether the lines are formed in the low density or the high density limit or in an intermediate range.