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OPTICAL AND UV OBSERVATIONS OF HERBIG-HARO OBJECTS

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ABSTRACT. Recent optical and ultraviolet (I.U.E.) observations of Herbig-Haro (H-H) objects are reviewed. We emphasize especially the importance of 1) accurate spectrophotometric data and 2) high dispersion spectra.

We discuss the range of emission line ratios occurring in different H-H objects and emphasize the drastic difference between the emission line spectra of "normal, high excitation" H-H objects and some extreme "low excitation" objects with very unusual spectra, indicating very low degrees of ionization and small Mach numbers outside the range of available models. The usual shock wave interpretation of the optical spectra is discussed and some remaining intriguing problems are pointed out.

The apparent contradiction between optical and uv emission line spectra is reviewed and its implications for the shock wave interpretation are discussed.

We present continuum measurements. We favor the two-photon hypothesis as an interpretation of the continuum, but we point out some remaining difficulties. The necessity to better clarify the role of dust scattering in and near H-H objects is emphasized. We investigate the influence of uncertainties in the ultraviolet extinction curve on the derived energy distribution.

A number of fundamental parameters derived from spectrophotometric data are discussed. Of special interest are the masses which cover a surprisingly small range of values and the "luminosities" which after including the uv radiation turn out to be surprisingly high.

I. INTRODUCTION

Since their discovery by Haro (1950, 1952) and Herbig (1951) Herbig-Haro (H-H) objects have been defined by their optical spectra and their optical appearance. Soon it became clear that these data are not only needed for the identification of H-H objects but that optical emission line and continuous spectra contain a wealth of information on H-H objects which is relatively easily interpreted and which gives us information about physical conditions in and near these objects. -Since 1980 information has also been obtained about the ultraviolet spectra of H-H objects (Ortolani and d'Odorico 1980, Böhm, Böhm-Vitense and Brugel 1981, Böhm-Vitense et al., 1982, Brugel, Shull and Seab 1982, Schwartz 1983) which in part supplements the optical information in a very useful manner, but which also leads to surprising apparent paradoxes.

It is well known that spectrophotometric studies of the optical emission line spectra (Böhm 1956, Osterbrock 1958, Haro and Minkowski 1960, Böhm, Perry and Schwartz 1973, Böhm, Siegmund and Schwartz 1976, Schwartz 1975, 1976, Dopita 1978a,b, Böhm and Brugel 1979, Adams, Strom and Strom 1979, Böhm and Mannery 1981b) have shown early that the ionization in a H-H object cannot be due to stellar radiation. (Böhm 1956, Osterbrock 1958, Haro and Minkowski 1960). Lines of neutral atoms and lines of ions of low ionization energy (like Ca^+) are much too strong. It was shown by Schwartz (1975) and confirmed by the development of detailed shock wave models by Dopita (1978b), Raymond (1979), Shull and McKee and others that the emission line fluxes originate in recombination regions of shock waves. This fact combined with the rather large (and mostly negative) radial velocities (cf. Herbig 1962, Strom, Grasdalen and Strom 1974, Münch 1977, Schwartz 1978, 1981, Mundt, Stocke and Stockman 1983) and especially the very large proper motions (Herbig and Jones 1981, Jones and Herbig 1982) pointing away from a T Tauri or Herbig Ae star form the background against which the spectrophotometric observations have to be seen.

In this paper we intend to discuss the extent to which observations can be understood in terms of the above picture. There can be no doubt that the introduction of the shock wave model was really the decisive breakthrough in understanding the optical spectra. A qualitative understanding of most optical spectrophotometric data no longer seemed to be a basic problem. However, the observation of H-H objects in the ultraviolet as well as more detailed optical observations have convinced us that we are still facing a number of important unsolved problems. To these we have to add the problems which have been known for a long time and which are not automatically resolved by the introduction of shock wave models in their present form. The strong polarization in some H-H objects, specifically in H-H 24A poses such a problem. (Strom, Grasdalen and Strom 1974, Schmidt and Miller 1979, Cohen and Schmidt 1981).

In the following chapters we shall discuss the present status of the emission line (chapter II), and continuum (chapter III) observations. In both cases we shall look at the whole wavelengths range from about 1200 Å to about 11000 Å. In chapter IV we shall consider the determination of basic properties (and parameters) of Herbig-Haro objects from spectra. In part we can use these results in order to simply identify the basic shock wave parameters. There are, however, also parameters which give us additional information. (The total visible mass and the total luminosity of a H-H object are examples of such additional quantities). In chapter V we shall discuss a number of intriguing unsolved problems. Obviously we shall be mostly concerned with the physical processes inside H-H objects and not with the very fundamental study of H-H objects as tracers of the bipolar flow from young stars (cf. Cantó and Rodríguez 1980, Königl 1982, Mundt, Stocke and Stockman 1983).

II. OBSERVATIONS OF EMISSION LINE SPECTRA

A. Optical and Near Infrared Lines. The outstanding property of the H-H line spectra is the large flux (relative to, say, Hβ) of the forbidden and permitted lines of neutral particles ([O I], O I, [C I], [N I]) and of ions of low ionization energy (Ca II, [Ca II], [Fe II], Mg II, [S II]).

Though the optical and near infrared spectra of all H-H objects seem to be qualitatively similar there are considerable quantitative differences between individual objects ranging from the well known "high excitation" H-H objects like H-H 1, H-H 2H, H-H 32A in which the flux ratio [S II] 6717/Hα lies in the range 0.16 (H-H 2H) to 0.34 (H-H 32A) (Brugel, Böhm and Mannery 1981b) to low excitation objects like H-H 7 in which this flux ratio is 2.8 (Böhm, Brugel and Olmsted 1983). For this reason it is necessary to obtain spectrophotometric data for a rather wide range of H-H objects.

This has been recognized by a number of investigators and we have now available such data for considerable number of such H-H objects ($\sim$ 30).

In table 1 we list recent spectrophotometric observations of H-H objects in the optical range. In a moderately large number of cases there are observations with at least two different

TABLE 1. Recent Optical Spectrophotometry of H-H Objects

Object	Instrument	Spectral Range	Resolution	References
H-H 1NW	5m-MCSP	3200-10830	20 Å	BSS 76, BBM 81a,b
	3m-IDS	3700-7200	∿7 Å, 13 Å	S 76
	AAT-IDS	3900-7400	13.4 Å at Hα	D 78b
	KP2.1-IDS	3600-7400	8.5 Å, 13 Å	BBM 81a,b
	MP2.2-IT	6450-6750	∿0.4 Å	SBM 83
H-H 1SE	3m-IDS	3700-5800	∿7 Å	S 76
	AAT-IDS	3900-7400	∿13.4 at Hα	D 78b
	5m-MCSP	3200-10830	20 Å	BBM 81b
H-H 2A	KP4m-IT	6300-6731	-	S 78
	5m-MCSP	3200-10830	20 Å	BBM 81a,b
H-H 2B	KP4m-IT	6300-6731	-	S 78
H-H 2C	AAT-IDS	3900-7400	13.4 Å at Hα	D 78b
	KP4m-IT	6300-6731	-	S 78
H-H 2E	KP4m-IT	6300-6731	-	S 78
H-H 2G	5m-MCSP	3200-10830	20 Å	BSS 76, BBM 81a,b
	AAT-IDS	3900-7400	∿13.4 Å at Hα	D 78b
	KP2.1-IDS	3600-5400	8.5 Å, 13 Å	BBM 81a
	MP2.2-IT	6450-6750	∿0.4 Å	SBM 83
H-H 2H	5m-MCSP	3200-10830	20 Å	BSS 76, BBM 81a,b
	AAT-IDS	3900-7400	∿13.4 Å at Hα	D 78b
	KP4m-IT	6300-6731	-	S 78
	KP2.1-IDS	3600-7400	∿8.5 Å, 13 Å	BBM 81a,b
	MP2.2-IT	6450-6750	∿0.4 Å	SBM 83
H-H 2L	AAT-IDS	3900-7400	∿13.4 Å at Hα	D 78b
	KP4m-IDS	6300-6731	-	S 78
H-H 3	AAT-IDS	3900-7400	∿13.4 Å at Hα	D 78b
	KP2.1-IDS	3600-7400	8.5 Å, 13 Å	BBM 81b
H-H 7	5m-MCSP	3200-10830	20 Å	BBM 80, BBO 83
	MP2.2-IT	6450-6750	∿0.4 Å	SBM 83
H-H 8	MP2.2-IT	6450-6750	∿0.4 Å	SBM 83
H-H 10	MP2.2-IT	6450-6750	∿0.4 Å	SBM 83
H-H 11	5m-MCSP	3200-10800	20 Å	BBM 80, BBO 83
	MP2.2-IT	6450-6750	∿0.4 Å	SBM 83
H-H 12	MP2.2-IT	6450-6750	∿0.4 Å	SBM 83
H-H 24A	AAT-IDS	3900-7400	∿13.4 Å at Hα	D 78b
	KP2.1-IDS	3600-7400	8.5 Å, 13 Å	BBM 81a,b
H-H 28	MP2.2-IT	6450-6750	∿0.4 Å	SBM 83
H-H 30	KP2.1-IDS	4800-7400	∿13 Å	BBM 81b
H-H 32A	5m-MCSP	3200-10830	20 Å	BBM 81a,b
	AAT-IDS	3900-7400	∿13.4 Å at Hα	D 78b
	MP2.2-IT	6450-6750	∿0.4 Å	SBM
H-H 32A,B,C	MMT-ES	6548-6731	0.5 Å	MSS 83
	MMT-MR-Ret.		-	
H-H 40	AAT-IDS	3900-7400	∿13.4 at Hα	D 78b
	KP2.1-IDS	3600-7400	∿8.5 Å, 13 Å	BBM 81b
H-H 43	AAT-IDS	3900-7400	∿13.4 Å at Hα	D 78b
	5m-MCSP	3200-10830	20 Å	BBO 83
H-H 46	AAT-IDS	3900-7400	∿13.4 Å at Hα	D 78a,b
H-H 47	AAT-IDS	3900-7400	∿13.4 Å at Hα	D 78a,b
H-H 49	AAT-IPCS	3500-7500	∿10 Å	SD 80
H-H 50	AAT-IPCS	3500-7500	∿10 Å	SD 80
H-H 54B	AAT-IPCS	3500-7500	∿10 Å	SD 80
H-H 54C	AAT-IPCS	3500-7500	∿10 Å	SD 80
H-H 56	AAT-IPCS	3500-7500	∿10 Å	SD 80
H-H 57	AAT-IPCS	3500-7500	∿10 Å	SD 80
H-H 101	AAT-IDS	3900-7400	∿13.4 Å at Hα	D 78b
Burnham's nebula	5m-MCSP	3200-10830	∿20 Å	S 74
	2.1-HCOSc			

NOTES:

BSS 76 = Böhm, Siegmund and Schwartz 1976.
BBM 81 = Böhm, Brugel and Mannery 1981, S74,76,78 = Schwartz 1974, 1976, 1978.
D 78 = Dopita 1978, SBM 83 = Solf, Böhm and Mundt 1983, BBM 81 = Brugel, Böhm and Mannery 1981, MSS 83 = Mundt, Stocke and Stockman 1983, B,B,O83 = Böhm, Brugel and Olmsted 1983, SD 80 = Schwartz and Dopita 1980.

instruments so that the data may be considered with some confidence. In general the spectrophotometrically best data have low spectral resolution. The wide spectral range of the MCSP observations is a great advantage. It permits a rather reliable determination of the reddening using Miller's [S II] method which requires flux determinations for the infrared lines [S II] 10317/10336 Å, in addition to the line fluxes of [S II] 4068/76 Å. Reliable information about the reddening is needed in order to give a convincing interpretation of the spectrophotometric data.

In order to get a feeling for the spectral differences between a high excitation object like H-H 2H and a typical low excitation object like H-H 7 we compare the fluxes of a number of lines observed in these two objects in table 2. The data have been corrected for interstellar reddening (E(B-V) $\sim$ 0.34 for H-H 2H, E(B-V) $\sim$ 0.62 for H-H 7, see below). The table shows clearly how large the differences in the relative line fluxes can become though both objects can be immediately recognized as H-H objects. Obviously the changes are especially large in Ca II 3933, [O III] 5007, [N I] 5198/5200, [O I] 6300/6363, [N II] 6584, [S II] 6717, [Ca II] 7291 and extremely large in the [C I] 9848 line.

TABLE 2. Comparison of Emission Line Fluxes in a High Excitation (H-H 2H) and a Very Low Excitation Herbig-Haro Object (H-H 7)

Identification	λ	F_λ(rel) H-H 2H	H-H 7
O II	3726/29	169	87
Ca II	3933	14	69
[S II]	4068/76	64	119
$H\gamma$	4340	34	74
[Fe II]	4414/16	6	9
Mg I	4571	4	9
$H\beta$	4861	100	100
[O III]	5007	63	$\sim$10
[Fe II]	5158	4	$<$20
[N I]	5198/5200	10	184
[O I]	6300	122	405
[O I]	6363	22	123
$H\alpha$	6563	293	447
[N II]	6584	154	23
[S II]	6717	48	1266
[Ca II]	7291	8	79
[O II]	7319		
[Ca II]	7324	67	44
[O II]	7330		
[C I]	9848	8	596
[S II]	10317	11	-
[S II]	10336	12	26

The spectra listed in table 2 are (at least at present) the extreme cases of a wide range of objects for which spectrophotometric data have been obtained now.

Some of the differences are surprisingly large. For instance, the flux ratio [C I] 9848/$H\alpha$ is $\sim$ 0.03 in H-H 2H and $\sim$ 1.33 in H-H 7. The flux ratio [S II] 6717/$H\alpha$ is $\sim$ 0.16 in H-H 2H and $\sim$ 2.8 in H-H 7. As we shall see below all observed line ratios in low excitation objects basically indicate low Mach number shocks, but in many cases their absolute values lie far outside of the range which occurs in theoretical predictions (Dopita 1977, 1978b, Raymond 1979, Shull and McKee 1979, see chapter IV). Further progress is to be expected from combining higher spectral and spatial resolution with high spectrophotometric accuracy. Presently some high resolution data are available which, however are mostly used in order to obtain radial velocity information (Schwartz 1978, Schwartz and Dopita 1980, Schwartz 1981, Solf, Böhm and Mundt 1983). In his pioneering work

Schwartz (see especially 1978, 1981) has measured the mean radial velocity and the velocity dispersion for different ions and interpreted them successfully in terms of shock wave models (see also chapter IV). Solf, Böhm and Mundt (1983) now have obtained high dispersion Coudé spectra of 12 H-H objects. The dispersion is ∿ 7.5 Å/mm and the resolution ∿ 0.4 Å. These observations include also rather faint objects like H-H 7, H-H 8, H-H 10 and H-H 12.

In figure 1 we show examples of recent high dispersion observations in H-H 1 and H-H 32A by Solf and Böhm. (Note the high spatial resolution!)

B. Observations of Ultraviolet Line Spectra. The discovery of ultraviolet radiation from H-H objects with I.U.E. (Ortolani and d'Odorico 1980, Böhm, Böhm-Vitense and Brugel 1981, Bohm-Vitense, Böhm, Cardelli and Nemec 1982, Brugel, Shull and Seab 1982, Schwartz 1983) was a considerable surprise for two reasons. First of all, even H-H 1 has only a visual magnitude of ∿ 15.7 so that it would be very difficult to observe it with I.U.E. unless it had a very large UV excess

Secondly, all H-H objects studied so far show at least moderate reddening (with an E(B-V) between about 0.3 and 0.7) and one would expect that, correspondingly, they would have rather high extinction in the uv. For instance, in a case in which E(B-V) = 0.5 (close to the value for H-H 1) we have a total extinction of ∿ 4.25^m at 1400 Å provided the extinction curve corresponds to Seaton's (1979) average galactic curve. It is obvious that this fact should make the detection of H-H objects with I.U.E. even more difficult. The explanation of the detectability of H-H objects must probably be attributed to two effects: 1) Strong intrinsic ultraviolet radiation from the shock fronts, 2) an extinction law which is probably more similar to the θ Ori curve (cf. Bohlin and Savage 1981) than to the average galactic curve. Such a curve leads to considerably less extinction below ∿ 2000 Å than the average galactic curve.

To the best of our knowledge so far 5 H-H objects have been observed in the UV with I.U.E. In addition the circumstellar environment of the Cohen-Schwartz star (Cohen and Schwartz 1979) has been observed (Böhm and Böhm-Vitense 1982). This region shows certain similarities to a faint H-H object. Some basic information about UV observations of H-H objects is listed in table 3.

TABLE 3. Ultraviolet (I.U.E.) Observations of H-H Objects

Object	Wavelength Region	References	
H-H 1	SW	O d'O 80	
	SW, LW	BBB 81, BBCN 82	
H-H 2	SW, LW	BBCN 82	Tried to get spatial resolution
	SW	BSS 82	Very long exposure
H-H 32	SW, LW	BB83	Very faint spectra
H-H 43	SW	S 83	Low excitation spectra, very
H-H 47	SW	S 83	different from H-H 1, H-H 2, H-H 32
Environment of C-S star	SW	BB 82	Only "H-H like" continuum, possible weak emission line spectrum different from H-H 1, H-H 2

NOTES:

O d'O 80 = Ortolani and d'Odorico 1980, BSS 82 = Brugel, Shull and Seab 1982, BBB 81 = Böhm, Böhm-Vitense and Brugel 1981, BBCN 82 = Böhm-Vitense, Böhm, Cardelli and Nemec 1982, BB 82, 83 = Böhm and Böhm-Vitense 1982, 1983, S 83 = Schwartz 1983. -SW = short wavelength range: 1200 Å $\lesssim \lambda \lesssim$ 1950 Å; LW = long wavelength range: 2100 Å $\lesssim \lambda \lesssim$ 3100 Å

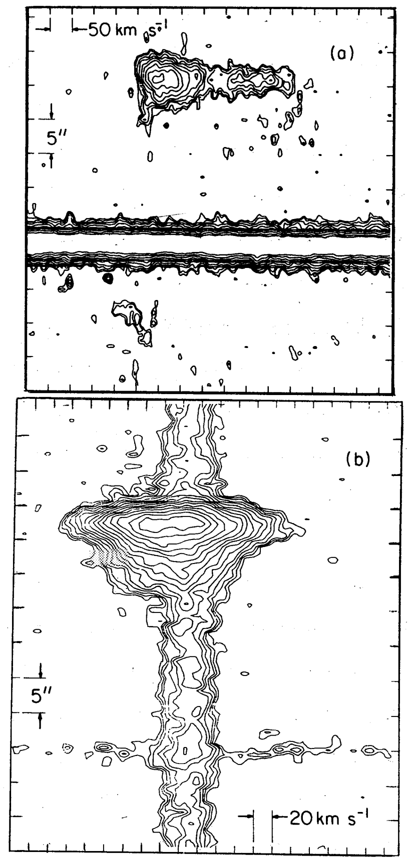

Figure 1. Contour lines showing line flux densities of the [N II] 6583 line in H-H 32(a) and the Hα line in H-H 1(b). The ordinate corresponds to the geometrical coordinate along the spectrograph slit, the abscissa to the wavelength. Two successive contour lines correspond to a flux ratio of $\sqrt{2}$. The stellar spectrum in (1a) is due to AS 353 A. -Based on Coudé spectra obtained at the 2.2m telescope of the Calar Alto Observatory by Dr. J. Solf and the author.

The spectra of "high excitation objects" (H-H 1, H-H 2, H-H 32) show emission lines, of which typically C IV 1547/1551, C III] 1909, C II] 2326 and Mg II 2796/2803 are the strongest ones. A considerable number of additional emission lines have been detected in H-H 1 and H-H 2 (Ortolani and d'Odorico 1980, Böhm, Böhm-Vitense and Brugel 1981, Böhm-Vitense, Böhm, Cardelli and Nemec 1982, Brugel, Shull and Seab 1982). Since flux measurements of faint lines in such faint objects are rather uncertain we present in table 4 the emission line uv spectrum of a fictitious "average high excitation H-H object" which we obtain by straight averaging over all observations of H-H 1 and H-H 2. Though the procedure is questionable the result may be of some interest. Some justification for the procedure may be derived from the fact that the four strong uv emission lines show almost identical (relative) fluxes in H-H 1 and H-H 2 (cf. Böhm-Vitense et al. 1982).

Table 4 immediately shows one surprising fact. The lines coming from rather highly ionized particles (C IV, C III, O IV, O III, Si IV, Si III) are surprisingly strong in contradistinction to the optical spectrum in which [O I], [S II] and [O II] belong to the strongest lines. We might expect that this fact will lead to difficulties in the interpretation of the spectra. (See chapter IV).

TABLE 4. Ultraviolet Emission Line Fluxes in the "Average High Excitation H-H Object"

Identification	λ	Rel. Flux (Hβ = 100)
O I	1302/13	77
C II	1335	113
Si IV	1394/1403	172
O IV	1405/1407	
C IV	1548/1551	419
He II	1640	55
O III]	1661/1666	159
N III]	1747/1754	74
Si II	1808/1817	55
Si III]	1892	52
C III]	1907/1909	236
C II]	2326	512
[O II]	2470	140
Mg II	2796/2803	216

In the observations of H-H 32 we seem to have reached the limit of I.U.E. observations in a single I.U.E. "shift" (∿ 7 hrs. of observing time). This is not surprising since H-H 32 is almost by a factor 2 fainter in the visual than H-H 1. Moreover, it has an E(B-V) ∿ .69 instead of the E(B-V) ∿ .47 for H-H 1 and .34 for H-H 2H. Only C IV 1547, C III] 1909 and Mg II 2800 could be detected in this object. (Böhm and Böhm-Vitense 1983).

An intriguing and unexpected result was recently presented by Schwartz (1983). The low excitation objects H-H 43 and H-H 47 show an ultraviolet emission line spectrum which differs completely from the line spectra of the "high excitation" H-H objects like H-H 1, H-H 2 and H-H 32A. The only line from an atomic ion seems to be the C II 1335 line. All other lines are lines from the Lyman band of H_2 which are selectively excited by fluorescence from Lyα (Schwartz 1983). It is surprising how different low excitation and high excitation H-H objects look in the ultraviolet whereas in the optical range in spite of quantitative differences the spectra still look qualitatively similar. Moreover, H-H 43 appears to be only a moderately low excitation object in the optical range. With the limited results which are available now it almost looks as if there were a discontinuous transition between the ultraviolet emission line spectra of high excitation and low excitation H-H objects.

C. The Continuum of Herbig-Haro Objects. Though the continuum of H-H objects had been seen already by Herbig (1951), spectrophotometric studies have become available only rather recently. The problem lies of course in the faintness of the continuum in the optical part of the spectrum. Only fairly recently did we succeed (Böhm, Schwartz and Siegmund 1974) to measure the continuum in the two brightest H-H objects H-H 1 and H-H 2H with rather moderate accuracy in the range 3300 Å $\lesssim \lambda \lesssim$ 8000 Å. Additional observations of the optical continua of H-H 1, H-H 2A, H-H 2B, H-H 2G, H-H 2H, H-H 3, H-H 24A, H-H 32A, were obtained by Brugel, Böhm and Mannery (1981b), and Dopita, Binette and Schwartz (1982). Very recently the continua of the low excitation objects H-H 7, H-H 11, H-H 43, H-H 47 also have measured (Dopita, Binette and Schwartz 1982, Böhm, Brugel and Olmsted 1983).

In contradistinction to the situation for the line spectra there seems to be no basic difference between the continuous spectra of "high excitation" and "low excitation" H-H objects. All observations show a relatively steep increase of F_λ towards shorter wavelength, a property which at first appeared to be very enigmatic. Unfortunately the signal-to-noise ratios which could be achieved at first (typically 5-10 in the most favorable spectral intervals, see Böhm, Schwartz and Siegmund 1974), was not quite satisfying. It was therefore a very important confirmation of the optical continuum measurements when in H-H 1 a strong uv continuum was found which rises steeply towards shorter wavelength and whose F_λ near 3000 Å fits, at least approximately the F_λ at $\sim$ 3300 Å determined from the 200 inch - MCSP observations (Böhm, Böhm-Vitense and Brugel 1981). A similar conclusion was drawn by Ortolani and d'Odorico (1980) who had only a SWP (1200 Å $\lesssim \lambda \lesssim$ 1950 Å) spectrum but saw that a smooth interpolation between F_λ at $\lambda \sim 1950$ and F_λ at $\lambda \sim 3300$ Å would be possible. In further studies (cf. Böhm-Vitense et al. 1982) the smooth connection between the measurements in the optical range and the I.U.E. measurements has been confirmed. Consequently it seems appropriate to discuss the ultraviolet (I.U.E.) and optical continua as a single phenomenon in this chapter.

Are the <u>relative</u> energy distribution of H-H continua all approximately equal? The present observations seem to indicate that this is not the case though the differences are not very large. Brugel, Böhm and Mannery (1981a) use a crude power law approximation $F_\lambda \propto \lambda^{-n}$ in the range 3600 Å $\lesssim \lambda \lesssim$ 8000 Å and find $n \sim 2.9$ for H-H 32A, $n \sim 2.6$ for H-H 1 and $n \sim 2.05$ for H-H 2A and H-H 2H.

The energy distributions depend of course fully on the reddening correction. We believe, however,that because of the use of Miller's [S II] method (which is basically reliable and has a wavelength base corresponding approximately to the wavelength range of our optical spectra) the extinction correction in the optical range are basically correct.

This agrees with the point of view of Dopita, Binette and Schwartz (1982) who also give a theoretical explanation (see below) for the differences.

As mentioned above, continua of low excitation H-H objects are basically similar to those of "high excitation" objects. Even in the very low excitation faint object H-H 7 the continuum has been measured now. (Böhm, Brugel and Omsted 1983). The low excitation object H-H 43 has a relatively strong continuum which can be measured rather accurately (Dopita, Binette and Schwartz 1982, Böhm, Brugel and Olmsted 1983). Using again an interpolation formula $F_\lambda \propto \lambda^{-n}$ we find $n \sim 4$ (Böhm et al. 1983, see also figure 2).

A comparison of the continuous energy distribution of H-H 1, H-H 2H, H-H 32A and H-H 43 is shown in figure 2.

In the uv the uncertainty of the extinction correction does cause some problems. As emphasized above the E(B-V) values for different H-H objects are known fairly well. The relative shape of the extinction curve in the uv, however, differs in certain regions of the galaxy, and especially in regions of recent star formation, from the average galactic curve (cf. Snow and Seab 1980, Bohlin and Savage 1981).

In figure 3 we compare the ultraviolet energy distribution of H-H 2H determined with the average galactic extinction curve (Seaton 1979) to the energy distribution of the same object corrected with θ Orionis extinction curve (Bohlin and Savage 1981). As this figure shows the

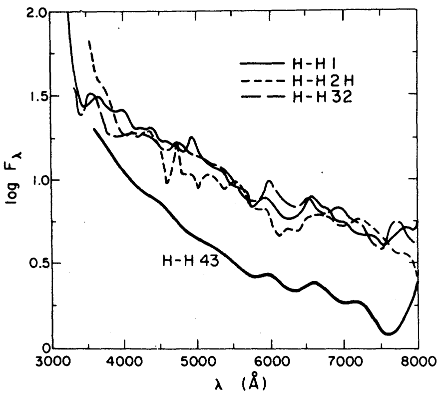

Figure 2. Average continuous energy distributions in the optical range for H-H 1, H-H 2H, H-H 32 and for the low excitation object H-H 43. F_λ is given in arbitrary units. (Based on data by Böhm et al. (1974), Brugel et al. (1981a), Böhm et al. (1983).

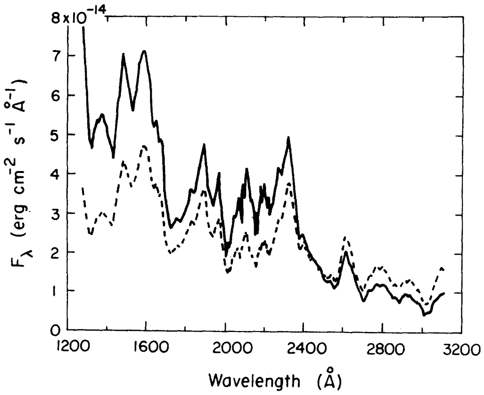

Figure 3. Average continuous energy distribution of H-H 2H in the ultraviolet, extinction corrected using the Seaton (1979) curve (solid line) and the θ Ori (Bohlin and Savage 1981) extinction curve. E(B-V) = 0.34 has been assumed in both cases.

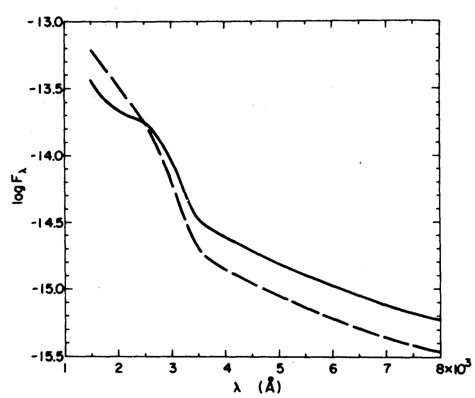

Figure 4. Smoothed energy distribution of the H-H 2H continuum in the range 1300 Å $\lesssim \lambda \lesssim$ 8000 Å, dereddened using the Seaton (1979) (dashes) and the Bohlin Savage (1981) θ Ori extinction curve (solid line). This is a slightly modified form of figure 3, published by Böhm-Vitense et al. in Ap.J. 262, 224 (1982).

θ Orionis extinction curve leads to a flatter energy distribution than the average galactic extinction curve but even the θ Ori curve leads to a rise of F_λ towards shorter wavelengths in the ultraviolet. In fact, considering the whole wavelengths range 1300 Å $\lesssim \lambda \lesssim$ 8000 Å (figure 4) we see that the wavelength dependence of F_λ is so strong that even the very different Seaton (1979) and Bohlin-Savage (1981) extinction curves lead to energy distributions which look qualitatively very similar. Consequently, we consider it as practically impossible to attribute the very surprising qualitative behavior of F_λ to the possible use of an incorrect extinction curve. We conclude from figure 4 that the continuous F_λ of Herbig-Haro objects definitely rises very steeply towards shorter wavelength but that the details, of course, depend on the shape of the extinction curve. For H-H 2 we consider the θ Ori extinction curve (Bohlin and Savage 1981) as more probably relevant than the average galactic curve (Seaton 1981). There can be little doubt that more detailed information about the extinction in the ultraviolet is needed in order to make more quantitative and reliable statements on the continuous ultraviolet energy distribution in Herbig-Haro objects.

Since at present the most promising theory of the continuum interprets it as a collisionally excited two-photon continuum (Dopita and Schwartz 1981, Dopita, Binette and Schwartz 1982, Brugel, Shull and Seab 1982, see below) the behavior of F_λ below 1400 Å is of great importance. The theory of the two-photon continuum (Spitzer and Greenstein 1951, Drake and Ulrich 1981) predicts a rather steep decrease towards shorter wavelengths below $\lambda \sim$ 1410 Å. Such a decrease is probably present (Brugel, Shull and Seab 1982) but it is not as clear and convincing as one would like to see it.

IV. BASIC PROPERTIES OF H-H OBJECTS DERIVED FROM OPTICAL AND ULTRAVIOLET SPECTRA

A. Emission Lines. We shall first describe a number of results which can be obtained from the spectroscopic data without referring directly to theoretical shock wave models. These are T_e and N_e for the line emitting regions, the degree of ionization, the total mass of the emitting region, the luminosity of the object (restricting ourselves, e.g., to 1200 Å $\lesssim \lambda \lesssim$ 11000 Å), the filling factors and the reddening (expressed as E(B-V)). For the T_e and N_e determination we have to assume that the excitation of the forbidden lines is due to electron collisions (cf. Böhm 1975, 1978b). For the mass determinations a spherically symmetric mass distribution inside the H-H condensation has to be assumed (as a crude approximation). E(B-V) has been determined using the [S II] method (Miller 1968).

The main results of these empirical determinations are given in table 5 which is based on results by Böhm, Siegmund and Schwartz 1976, Brugel, Böhm and Mannery 1981b, and Böhm, Brugel and Olmsted 1983. A number of the quantities obviously are basically related to the selection of the correct shock wave model (cf. Dopita 1978b, Raymond 1979, Shull and McKee 1979). The average ionization and the average T_e and N_e in the line forming regions are of this type. From a theoretical point of view they are all determined in principle once the pre-shock density and the shock Mach number is known. The small filling factors are obviously a consequence of the fact that for the typical pre-shock densities and the Mach numbers the thickness of the recombination regions is much smaller than the extension along the shock surface. E(B-V) and A(Hβ) give us information

TABLE 5. Range of Basic Parameters in 12 H-H Objects and Individual Condensations

r(a.u.)	Average Ioniz. $X_{HII}/(X_{HI}+X_{HII})$	T_e(K)	N_e(cm^{-3})	Filling Factor (H)
300-2000	0.07 - 0.80	7500-12000	$2.5x10^3$-$5.5x10^4$	$2x10^{-3}$-$68x10^{-3}$

L (1200-11000 Å)	M (Earth Masses)	E(B-V)	A(Hβ)
0.1-1.4$L_{\odot}$	2 - 34	0.34 - 0.71	1.31 - 2.73

about the imbedding of H-H objects in clouds. We find the "luminosities" and masses especially interesting. It is surprising that the visible masses of H-H objects all lie in the range of a few to a few tens of earth masses. Unless some unidentified selection effect is contained in our choice of H-H objects this result should be explained by the theory of H-H objects. As far as I can see there has not even been an attempt in our present shock wave interpretation of H-H objects to find such an explanation. -At first sight the "luminosities" (restricted to the range 1200 Å $\lesssim \lambda \lesssim$ 11000 Å) seem to be surprisingly high for the small masses of the objects. On the other hand, the kinetic energy of 10 earth masses moving with 100 km s^{-1} would be $6x10^{42}$ ergs. This would be sufficient to give such an H-H condensation 1$L_{\odot}$ for 50 years provided it were possible to convert 100% of the kinetic energy into radiation (only) in the range 1200 Å $\lesssim \lambda \lesssim$ 11000 Å. This assumption is certainly much too optimistic. We conclude that it will be hard to understand the high luminosities of the H-H objects, but that (fortunately) the discrepancies seem to be roughly one order of magnitude and not many. We should remember that the high luminosities are mostly due to the high ultraviolet radiation of H-H objects (Böhm, Böhm-Vitense and Brugel 1981) so some revision may be necessary once the information about the ultraviolet extinction curve improves. However, we do not believe that this could lead to "luminosity" changes of more than a factor 2-3.

It is well known (Schwartz 1975, 1978, Dopita 1978, Raymond 1976, 1979, Shull and McKee 1979, Böhm 1978a,b, Shull 1982) that the present (plane-parallel) shock wave models can explain the basic properties of the optical spectra of all but the lowest excitation objects (which include H-H 7, H-H 11, H-H 43, H-H 47) rather well. The largest difficulties occur in the lowest excitation objects. Comparing the observational results (Böhm, Brugel and Olmsted 1983) for, e.g. H-H 7 to the theoretical results for shock waves of different Mach numbers (e.g. Shull and McKee 1979) the large [S II] 6717/Hα, [N I] 5200/Hβ and [C I] 9848/Hα ratios as well as the absence of [0 III] 5007 make it quite obvious that the corresponding shock wave must have rather a small Mach number. From Shull and McKee's (1979) tables it is clear that the shock velocity must be considerably lower than the lowest value (namely 40 km s^{-1}) for which they have calculated a model (e.g. the model gives a [S II] 6717/Hα flux ratio 0.74 whereas we measure 2.83). A similar though not quite so drastic situation exists for the ratio of [0 I] (6300+6363)/Hα. The prediction for this ratio is 0.74, we observe 1.18.

The question which we cannot yet answer is: 1) Would a model of lower Mach number explain the optical emission line observations? 2) If so, which shock velocity would be appropriate? At the present time we have no answers to these questions yet. We have the feeling that it will, e.g. be very difficult to explain the very large [S II] 6717/Hα and the [C I] 9848/Hα ratios.

The most serious problem which we encounter in the explanation of emission line spectra of H-H objects is the apparent discrepancy between the rather low ionization indicated by the optical spectra (Böhm, Siegmund and Schwartz 1976, Dopita 1978b, Brugel, Böhm and Mannery 1981b), and the rather high ionization indicated by the ultraviolet lines (Ortolani and d'Odorico 1980, Böhm, Böhm-Vitense and Brugel 1981, Böhm-Vitense et al. 1982). In the optical range the [O I] 6300 and the [O II] 3726/29 lines are both stronger than the λ5007 line of [O III] whereas in the ultraviolet C IV 1548/1551 is very strong and the Si IV and O IV lines are strong. This apparent contradiction is reflected in the fact that shock wave models (Dopita 1978a, Raymond 1979, Shull and McKee 1979) which have been selected to explain the optical spectra predict ultraviolet C IV, Si IV and O IV lines which are fainter by more than a factor 100 than the observed lines. Unfortunately this discrepancy cannot be simply avoided by superposing two or more shock waves. Any shock wave which would lead to strong C IV, Si IV and O IV] emission in the ultraviolet leads e.g. to very strong [O III] emission in the optical and thereby destroys the agreement between theory and observation in this range. -Strangely the Mg II 2796/2803 lines are also considerably stronger (∿ factor 7) than models fitted to the optical spectra would indicate. (If we were asked to find a shock wave model for the Mg II lines only a model of rather low shock velocity would be appropriate.)

B. Continua. It has recently been suggested to interpret the observed optical and ultraviolet continuum as a collisionally enhanced two-photon continuum of hydrogen (Dopita, Binette and Schwartz 1982, Brugel, Shull and Seab 1982). This suggestion looks promising though some problems remain. If correct, F_λ should rise towards shorter wavelengths until it reaches a maximum near $\lambda \sim 1410$ Å (Spitzer and Greenstein 1951, Drake and Ulrich 1981). From there F_λ must decrease very steeply towards shorter wavelengths so that it disappears at Lα.

There seems to be agreement about the fact that the observed F_λ of the typical H-H continuum increases in general (excluding some intermediate "humps") steeply towards shorter wavelength from, say, $\lambda \sim 8000$ Å to at least $\lambda \sim 1550$ Å (Ortolani and d'Odorico 1980, Böhm, Böhm-Vitense and Brugel 1981, Böhm-Vitense et al. 1982, Brugel, Shull and Seab 1982). All observations show an (intermediate?) maximum at $\lambda \sim 1550$ Å. Ortolani and d'Odorico (1980), Böhm, Böhm-Vitense and Brugel (1981) and Böhm-Vitense et al. (1982) concluded from their observations that F_λ starts to increase again below ∿ 1350 Å. Brugel, Shull and Seab (1982) reduced the noise in the F_λ measurements by obtaining a longer exposure (430 min) of H-H 2H. They also made a special effort to identify and eliminate from the continuum more emission lines than had been done before. They conclude that below 1500 Å, the continuum F_λ does continue to decrease as far as it can be measured at all.

These measurements are very difficult with I.U.E. and it may not be possible to reach a final conclusion at the present time. However, since the optical F_λ also seem compatible with a two-photon continuum (Dopita, Binette and Schwartz 1982) the hypothesis is indeed promising and should be pursued. Especially the continuum of H-H 43 (a low excitation object, see above) which is relatively strong and can be measured with rather high accuracy agrees well with the predictions for the two-photon continuum (Dopita, Binette and Schwartz 1982, Böhm, Brugel and Olmsted 1983).

There are, however, also a few facts which make the acceptance of the 2-photon hypothesis somewhat more difficult. At $\lambda \sim 1680$ Å there is a sort of discontinuity (or at least a very steep rise towards the ultraviolet) which is certainly not contained in the prediction of the two-photon continuum. Brugel, Shull and Seab (1982) assume that this is an (as yet unidentified) absorption feature. This is certainly possible but it makes the explanation of the continuum less straightforward. A further point which may be relevant to this problem is the following. The environment of the Cohen-Schwartz star emits an ultraviolet continuum which looks rather similar to an H-H continuum. (However, the emission line spectrum is different and considerably fainter than in H-H objects.) This continuum increases even more steeply towards short wavelengths than in H-H 1 and H-H 2 and we have the impression that it definitely continues to rise for $\lambda <$ 1400 Å (Böhm and Böhm-Vitense 1982, 1983b) for all reasonable assumptions about the reddening. Again, however, the spectra are very noisy and the uncertainties in F_λ are considerable.

V. SOME UNSOLVED PROBLEMS

A. Emission Line Problems. As emphasized above the most fundamental unsolved problem seems to be the apparent contradiction between the large ionization indicated by the large flux in the ultraviolet emission lines of C IV, Si IV, O IV and the rather small ionization (cf. Brugel, Böhm and Mannery 1981b) determined from optical spectra. This leads to the suspicion that the uv lines which are mostly permitted and semiforbidden lines may be formed in regions of relatively high density which do not contribute to the formation of the optical forbidden lines. However such a hypothesis encounters many difficulties, e.g.:

1) there are also permitted lines (e.g. Ca II H and K) in the optical range indicating a very low degree of ionization;

2) ultraviolet and optical lines lead to approximately the same emission measure, probably indicating that they are formed in the same region;

3) as far as we can tell, position and image size are the same in the ultraviolet as in the optical range.

The difficulties are exhibited in a more quantitative way by the fact that (plane-parallel) shock wave models which explain the optical spectra reasonably well predict C IV, O IV and Si IV lines which are by $\sim 10^2$ lower than observed. Even the predictions for C III] 1909 are by about a factor 10 too low. There are also other, not quite so drastic problems, e.g. the unexpectedly large flux in the Mg II 2800 lines. Other discrepancies, e.g. the too large flux in the C II] 2326 line (see also Brugel, Shull and Seab 1982), are sufficiently small that they may be resolved once we have better information about the ultraviolet extinction curve.

There are a few other problems connected with the shock wave interpretations of which we would like only to quote one which is very intriguing: the proper motions of H-H objects indicate velocities up to 350 km s^{-1} (Herbig and Jones 1981), radial velocities in some cases reach similar values (Münch 1977, Herbig 1961, 1978, Mundt, Stocke and Stockman 1983). One might expect that at least in a few cases one might see shock velocities of this order of magnitude (this would be true e.g. in Schwartz' (1978) shocked cloudlet model). On the other hand the relatively bright well-known H-H objects like H-H 1, H-H 2H, H-H 2G, H-H 2A, H-H 32A all lie in an extremely narrow range of shock velocities between 80 and 90 km s^{-1}. (We refer to the spectrum predictions by Shull and McKee, similar though slightly shifted results follow from the calculation by Raymond (1976, 1979) and Dopita (1978b)). The reason for this somewhat strange result lies in the fact that in the model calculations the relative fluxes of e.g. the [O II], the [N II] and especially the [O III] lines are very sensitive functions of the shock velocities whereas surprisingly the ratios of these lines to, say, Hβ all lie in rather narrow ranges. In fact, after having seen the results of shock wave calculations we realize that it is quite surprising that the spectra of "high excitation objects" are so similar to each other. (For instance we see that, from a theoretical point of view, it is quite surprising that they all have [O III] 5007 fluxes which are roughly comparable to those of Hβ.)

Another interesting fact whose theoretical implications we do not yet fully understand is the drastic difference between the ultraviolet spectra of high excitation objects (strong C IV, C III, Si IV, O IV, C II lines) and low excitation objects (almost only selectively excited lines of the H_α Lyman band. If there are also intermediate spectra they have not yet been found. What do they look like?

B. Continuum Problems. As shown in the last chapter the most urgent problem in this field is a final clarification of the role of the two-photon continuum of hydrogen in H-H objects. We showed above that there are strong indications that the 2-photon continuum can explain essential aspects of the observations but that some problems remain.

In this context we also have to reconsider the role of dust scattering and polarization in H-H continua (Strom, Grasdalen and Storm 1974, Strom, Strom and Kinman 1974, Schmidt and Miller 1979, Cohen and Schmidt 1981). There are a few cases of H-H objects in which the linear polarization is considerable and the polarization angle is compatible with dust scattering of a T Tauri continuum. Brugel, Böhm and Mannery (1981a) have pointed out that in a considerable number of H-H objects the continuous energy distribution does not seem to be compatible with the idea that the continua are formed by dust scattering of light from T Tauri stars. This becomes even more obvious from a study of the continuum in the ultraviolet. On the other hand in some objects the observed polarization is considerable. How do we resolve this paradox? Is the polarization possibly generated in a process other than dust scattering? Or is it sufficient to "mix" contributions from a 2-photon continuum formed "in situ" and a dust scattered T Tauri continuum in order to explain the observations. In order to learn more about dust particles in regions in which H-H objects are present Cardelli and Böhm (1983) have begun a study of the reflection properties of NGC 1999.

Another unsolved problem is connected with the X-ray detection of the H-H region by Pravdo and Marshall (1981). What is the relation of this radiation to the uv continuum?

C. Fundamental Properties and Energy Balance. As mentioned above at least a subclass of H-H condensations all have (very approximately) masses of the order of 10 earth masses. This is intriguing. H-H objects do not look like arbitrary chunks of stellar wind matter. Of course there is the possibility that an unidentified selection effect is present. If this, however, should not be the case we may be able to obtain useful information on scales of instability in the stellar wind.

As indicated above the luminosity of bright objects like H-H 1 and H-H 2H seems to be surprisingly large (∿ $1L_{\odot}$ even if we restrict outselves to the λ-range 1200 Å - 11000 Å). Such objects seem to radiate away more energy during their lifetime than they contain in the form of kinetic energy. This seems to exclude all models in which matter is accelerated once and the kinetic energy is then used to maintain the radiating shock. (See also the detailed discussion by Mundt and Hartmann 1983.) A quantitative model which takes into account these facts has not yet been developed.

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DISCUSSION

Carrasco: Perhaps the coincidence of enhanced scattered light in HH-objects is due to evaporation of accreted mantles in the dust where the shock is proceeding. Maybe the albedo of the cores and mantles is different.

Böhm: I agree that this is possible.

S. Strom: I find from our monochromatic photographs that the relative contribution of scattered light and pure emission spectra vary radically from object-to-object and within a given complex. I suspect that the objects you have looked out with *IUE* are almost certainly shock emission-dominated and fall in that class which, at optical wavelengths, show little or no scattered light continuum.

R. Schwartz: (*Comment*) In comparing theoretical shock calculations with observed line intensities, we must bear in mind two fundamental limitations of present models. (1) They are plane-parallel in geometry, and the morphology of HH's strongly suggests that the shocks are non-planar. This could account for some of the discrepancies. (2) Present shock models deal only with atomic pre-shock gas as applied to HH's. We do not know how a substantial fraction of H_2 in the pre-shock gas might effect the appearance of shocks with velocities around 100 km s^{-1}.

Böhm: I agree that this is true. However, I do feel that the apparent contradiction between the optical and *UV* line spectra is probably more difficult to resolve. I think it can be simply expressed as a contradiction between the degrees of ionization determined from optical and from *UV* lines.

Mundt: (*Comment*) The continuous *UV* spectra of HH 1, HH 2 and the C-S star environment are probably severely contaminated by emission from the Orion reflection nebulosity. Its brightness in the vicinity of these objects is roughly known from OAO-2 measurements. Although its exact contribution is not well known, (within a factor of 2) due to spatial variations in its brightness, the OAO-2 data indicate contributions for $\lambda \lesssim 1500$ A of about 30-50% to HH 1 - 2. The data suggest that the *UV* continuum in the environment of the C-S star can be fully accounted by the light from the Orion reflection nebulosity. This subject is discussed in more detail in a paper submitted to *Ap. J.* (*Letters*) (together with A. Witt).

Herbig: As I recall Raymond's calculations of gas flow through a plane shock, the recombination region extends downstream for a distance that, if at 500 pc and flowing in the plane of the sky, corresponds to about 1". Is it possible that the conflict between the excitation levels of ultraviolet and visual region lines is due to the mixing of these various spectra; i.e., to our present inability to resolve them?

Böhm: It is true that these different regions cannot be resolved. However, all predictions of line fluxes refer to the integrated contributions from the whole shock wave (and recombination regions) and are therefore applicable.

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