Part I: General Description

Abstract

Background information is presented on the Herbig-Haro nebulosities observed with the IUE until the end of the mission. The log of observations and the UV spectrum are provided for all the objects. This information is completed with basic data on the individual sources.

1 Introduction

Herbig-Haro Objects (HHOs) are shock-excited nebulosities observed in star forming regions. They are powered by the energy released in the shocks between outflows from pre-main-sequence stars and interstellar gas (or previous ejecta). They were discovered in the Orion region by George Herbig and Guillermo Haro in the late forties. Ambartsumian (1954, 1957) called these nebulosities HHOs and suggested, for the first time, that they may be related with star formation. A recent review on these 50 years of HHOs research can be found in Reipurth & Heathcote (1997).

The IUE was well suited to study HHOs because shock waves emit strong lines (resonance and semiforbidden) in the UV range. However the detection of HH 1 with the IUE (Ortolani & D'Odorico, 1980) was somewhat surprising since HHOs were expected to be heavily extincted and moreover, the shock wave models available at the beginning of the IUE mission (Dopita 1978, Schwartz 1978, Raymond 1979) predicted lower line fluxes than what, at the end, was observed with the IUE.

During the IUE lifetime (1978-1996) up to 19 HHOs were observed (see Sect. 4) but only 11 were actually detected, in fact, rather sophisticated extraction (and observation) techniques were used to detect 3 of them namely, HH 7, HH 11 and HH 29 (Cameron & Liseau, 1990, Liseau et al 1996). The following is just a brief summary of the UV spectral characteristics of the HHOs (as measured with the IUE) and of the main contributions of the IUE to this research field.

1.1 The UV spectrum of the HHOs

The UV spectrum of the HHOs consists of a continuum which rises towards short wavelengths and some emission lines (typically of C IV, Si III], C III], C II] and Mg II as well as of molecular hydrogen).

1.1.1 Lines

The lines observed in the UV spectra of the HHOs depend on the degree of excitation of the nebulosity. High excitation objects like HH1 or HH2 produce strong emission lines of CIV (UV1), OIII](1663), SiIII](1892) and CIII](1909) in the short wavelength range (1200-2000 Å) (Ortolani & D'Odorico 1980, Bohm et al 1981, Brugel et al 1982, Bohm-Vitense et al 1982). However, low excitation objects like HH43 or HH47 are characterised by the presence of the H_2 Lyman band emission lines (Schwartz, 1983, Schwartz et al 1985). In the long wavelength range (2000-3200 Å) lines of CII](2326), [OII](2470) and

Table 1: UV lines observed in HHOs

λ (Å)	Specie	$F_\lambda/F(H\beta)$ HH1[a]	HH43[b]
1258	H_2		77
1272	H_2		168
1303	OI	96	
1335	CII	186	
1403	SiIV,OIV	300	
1431	H_2		136
1446	H_2		195
1490	H_2		177
1505	H_2		222
1530	SiII	207	
1547	H_2		91
1550	CIV	352	
1562	H_2		145
1640	HeII	95	
1663	OIII]	149	
1750	NIII]	125	
1808,1817	SiII	71	
1909	CIII]	153	
2326	CII]	374	258
2470	[OII]		34
2800	MgII	163	82
2968	CI]		77

[a] from Bohm-Vitense et al 1982.
[b] from Schwartz et al 1985.

MgII (UV1) are observed in both types of objects (Bohm et al 1981, Bohm-Vitense et al 1982, Schwartz et al 1985, Cameron & Liseau 1990). The strength of these lines relative to Hβ is indicated in Table 1 for two prototypical objects: HH1 and HH43.

Emission lines have been detected with the IUE only for some few objects, namely, HH1 (Ortolani & D'Odorico 1980, Bohm et al 1981, Bohm-Vitense et al 1982), HH2 (Brugel et al 1982, Bohm-Vitense et al 1982), HH7 (Cameron & Liseau 1990), HH11 (Cameron & Liseau 1990), HH29 (Cameron & Liseau 1990), HH32 (Bohm & Bohm-Vitense 1984), HH43 (Schwartz 1983; Schwartz et al 1985) and HH47 (Schwartz 1983); only the MgII line was detected in HH7 and HH11. Therefore, the IUE sample reduces to 6 objects for line emission studies.

The lines are variable. Variability studies have been carried out for HH1 (Brugel et al 1985, Bohm et al 1993), HH2 (Bohm et al 1993) and HH29 (Cameron & Liseau 1990, Liseau et al 1996).

The spatial structure of the line emission region was resolved with the IUE for a few objects. Detailed studies on this structure can be found for HH1 and HH2 (Bohm-Vitense et al 1982, Bohm et al 1987, Lee et al 1988, Bohm et al 1993, Moro-Martín et al 1996), HH32 (Lee et al 1988, Moro-Martín et al 1996) and HH43 and HH 47 (Bohm et al 1991).

1.1.2 Continuum

The UV continuum of the HHOs is strong. As an example, the luminosity radiated by HH1 in the UV continuum is $\sim$ 76 % of the solar luminosity and about a factor of 14 higher than the energy emitted within the (3200-11000 Å) spectral range (Bohm et al 1981).

The UV continuum rises steeply towards short wavelengths, at least down to 1300 Å. The continuum has a detailed structure with some peaks between 1300 Å and 1800 Å and with a quite steep maximum at 1580 Å (Schwartz 1983, Bohm et al 1987, Bohm et al 1991). The overall spectral energy distribution is similar in high excitation objects like HH1 or HH2 and in low excitation objects like HH43 and HH47 (Schwartz 1983, Bohm et al 1987, Bohm et al 1993). The qualitative behaviour of the continuum seems to be quite insensitive to different types of extinction curves although a curve without the 2200Å feature seems to be the best approximation applicable, at least to HH1 and HH2 (Bohm-Vitense et al 1982). By the late 80's consensus was reached that the θ-Ori curve provides the best correction (Schwartz et al 1985, Bohm et al 1987). However, the uncertainties to be applied in the interestellar reddening law are still large and make the determination of the emission mechanism difficult.

The continuum is variable. Detailed studies of the continuum variability are only available for HH 29. A long term monitoring between 1986 and 1994 showed that the variations of UV continuum in the 1300-1900 Å range are correlated with the variations of the high ionization species, whereas the variations from low-ionization species appear anticorrelated (Liseau et al 1996).

The spatial distribution of the UV continuum was first studied by Lee et al (1988) and compared with the optical data for HH1, HH2, HH24, HH43 and HH47. They found that the UV continuum distribution in the long wavelength range (2000-3200 Å) is quite narrow and comparable to that in the optical, while that in the short wavelength range (1300-1950 Å) is broader than any emission line (UV or optical). Further studies of these objects were carried out by Bohm et al (1993) and Moro-Martín et al (1996).

1.2 The contribution of the IUE to the understanding of the HHOs

From the very first UV observation of HH1 two intriguing characteristics of the HHOs became evident: (1) the UV lines spectrum shows a higher degree of ionization than the optical spectra, and (2) the UV continuum rises to short wavelengths (at least up to 1300 Å). Most of the IUE observations were intended to find a physical explanation for these characteristics. The evolution from planar shock-wave models to bow-shock models in order to explain the spectrum of the HHOs occurred during the IUE lifetime. The physical mechanism which generates the UV continuum of HHOs is still uncertain. The following is just a brief accounting of the IUE major contributions.

1.2.1 Shock-wave models

- from planar to bow shocks

  Prior to the launch of IUE, the optical emission line spectra of the HHOs were attributed to the radiation from the cooling regions of planar shock wave (Dopita 1978, Schwartz 1978, Raymond 1979). Some features of the visual spectra were well accounted for by these models although the agreement was less satisfactory than that obtained for supernova remnants. The first IUE observations of HH1 (Ortolani & D'Odorico 1980, Bohm et al 1981) pointed out that planar shock waves models cannot simultaneously explain the optical and the UV spectrum of the HHOs. For instance, the small ratio between the $[OIII]_{5007}$ and the $[OII]_{3728}$ optical lines implies relatively small shock Mach numbers, but for these small values the flux of th CIV_{1550} lines is predicted to be ~ 2 orders of magnitude smaller than observed. Bohm et al (1981) suggested that UV lines could be formed in a denser region than the optical *"probably due to a different, higher density shock wave"*; later on this suggestion was shown not to be very plausible since the optical and UV lines of HH1 and HH2 are formed in the same region (Bohm-Vitense et al 1982). Brugel et al (1982) were the first to interprete these characteristics as a consequence of having a range of velocities in the shock wave; they pointed out that this velocity range arises naturally in bow-shocks which are expected to be produced if the HHOs are shocked cloudlets (Schwartz & Dopita 1980).

  In 1983, the first low excitation HHOs (HH43 and HH47) were observed (Schwartz, 1983). No high excitation lines of CIV or CIII] were detected and the far UV spectrum was found to be dominated by the H_2 Lyman band emission lines. The UV (as well as the IR) data could be explained by low-velocity (≤ 35 km/s) planar shocks (Dopita et al 1982).

  In 1984, the first bow-shock models were applied successfully to the UV and the optical spectra of an HHO (HH1 and HH2) (Hartmann & Raymond 1984, Brugel & Shull, 1984). In these models the bow-shock is approximated by a series of oblique plane shocks. The first theoretical predictions for the spatial distribution of emission in bow shocks became available soon after (Raga & Bohm, 1985, 1986, Hartigan et al 1987) and then, detailed studies on the spatial structure of the UV spectrum began. Bohm et al (1987) carried out the first analysis about the spatial distribution of the line emission (CIV, CIII], SiIII]) in HH1 and HH2. They found that, in general, the size of the CIII] and SiIII] emitting regions is slightly larger than the size of the CIV as predicted by the theoretical models. A more complete study making use of data from 6 HHOs confirmed this behaviour (Lee et al 1988). Also a detailed comparison between optical (H_α and [SII]) and UV (CIV, CIII], CII] and Mg II) lines showed that the size of the UV line emitting region is comparable to the optical size of the object (for instance in H_α) and that the UV emission line region is centered in the optical object.

  The fluorescent H_2 emission lines of low excitation HHOs (HH43 and HH47) were also found to be formed in narrow (unresolved) regions with characteristic sizes of at least a half of the optical ([SII]) emission region (Bohm et al 1991).

  By the end of the IUE mission, Moro-Martin et al (1996) showed that, in general, the parameters obtained from optical spectra provide a self-consistent picture when used to explain the UV data. The remaining differences between models and observations are attributed to the effect of complex preionization structures. Accurate calculations of the ionization state of the material entering the bow-shock had already shown the significance of pre-ionization for shock speeds of $\sim$ 150 km/s and below (Raymond et al 1988).

- Clumpiness and non-stationarity

  In the mid-time, UV variability studies showed up rapid variations in the UV emission-line spectrum of HH1 which were not accompanied with analogous optical changes (Brugel et al 1985). The relevance of the medium clumpiness was put forward. This was confirmed some years later from the detailed analysis of HH29 variability (Cameron & Liseau 1990;Liseau et al 1996). In particular, Liseau et al (1996) showed that the flux variations of the UV forbidden lines from low ionization species are anticorrelated with the variations of the short wavelength continuum and the variations of the high excitation species. Such behaviour is consistent with HH29 changing is degree of excitation with time. The combination of optical and UV data drove them to suggest a 2 phase model with a component at $T=10^4$ K and $N_e = 10^3$ cm^{-3} and a hot and dense component with $T=10^5$ K and $N_e = 10^6$ cm^{-3} with a very small filling factor ($\sim 0.1 - 1$ %). They suggested a variability time scale of some weeks and a non-stationarity and non-homogeneity of the flow.

1.2.2 The continuum problem

Prior to the lauch of IUE it was known that the continuum of the HHOs rises towards short wavelengths (Bohm et al 1974). Two possible explanations were suggested: (1) scattered light from nearby stars and (2) two photon emission from a hot shocked gas. The UV observations showed that the continuum rises steeply towards the shortest wavelengths observable with the IUE ($\sim$ 1300 Å). Therefore the UV continuum energy distribution cannot be explained by a T Tauri stellar continuum scattered by the dust. Mundt and Witt (1983) suggested that, at least for HH1 and HH2 (which are in the Orion region), there could be a contamination of the UV spectra by the Orion Reflection Nebula which could account for as much as 30 -50 % of the continuum flux at $\lambda \leq 1500$Å. However detailed analysis, in which the nebular background contribution was properly substracted out, showed a similar structural shape of the continuum, rising towards short wavelengths (Lee et al 1988). Therefore, it became clear that the peculiar spectral distribution of the UV continuum is not caused by scattered light from nearby stars.

The possible influence of the extinction curve on the continuum was discussed at length. The best correction was shown to be a θ-Ori extinction curve for HH43 (Schwartz et al 1985) and also for HH1 and HH2 (Bohm et al 1987). Therefore Cameron & Liseau (1990) introduced a UV colour index which is extinction-free for dust constituents giving rise to the θ-Ori extinction curves. This index was used to compare the observed continuum values with those calculated for a recombining hydrogenic plasma. With the possible exception of HH11, they found large deviations from the 2-photon decay continuum of HI. They also found that H_2^+ free-bound emission does not offer a solution to the continuum problem. In fact, previous studies had already shown that the short wavelength UV continuum has a maximum around 1580 Å but not near 1410 Å where the two photon continuum of hydrogen peaks (Bohm et al 1987).

A new key was provided by the discovery of the differences between the spatial distribution of the UV continuum in the long (2000-3200 Å) and in the short (1300-1950 Å) wavelength ranges (Lee et al 1988). The long wavelength continuum is quite narrow and comparable to the optical; both can be basically produced by the two photon decay mechanism. However, the short wavelength continuum is broader than any emission line (UV or optical) pointing out that an additional continuum formation mechanism is present.

At the end of the IUE mission, the most likely mechanism for the formation of this short wavelength continuum was believed to be H_2 *continuum* emission (Dalgarno et al 1970). Bohm et al (1987) realised that the observed UV continuum enhancement occurs only in the wavelength interval in which H_2 emission should occur and proposed this mechanism to explain the HH1 and HH2 spectra. In fact, this mechanism is also suitable to explain the close similarity between the structural shape of continuum in low and high excitation HHOs (Schwartz 1983, Bohm et al 1991); the H_2 continuum is formed in the destruction process of H_2 molecules which can be caused either by photodissociation by radiation shortwards of 912 Å or by collisions with low energy thermal particles. Unfortunately, there is not a complete agreement between the detailed spectral shape of the H_2 continuum and the UV data (even qualitative). Therefore, the physical mechanism which generates the short wavelength UV continuum of HHOs is still uncertain.

2 Background information on IUE spectra of TTS

The Reipurth (1997) Catalogue (RC) contains about four hundred HHOs and is the most complete and up-to-date compilation; only 19 of them were observed with the IUE. A complete list can be found at the end of this introductory section, together with some general information as the 1950.0 ecuatorial coordinates, the exciting star, the molecular cloud to which the star is associated, the excitation characteristics of the HH object (high excitation object:HEO or low excitation object:LEO), and the number of low dispersion spectra obtained with the LWP, LWR and SWP cameras.

In order to facilitate work with this catalogue we provide for each HHO a list of general information followed by a list with the available IUE observations. Then we describe in detail the IUE observations classified by subsets obtained at the same location on the nebulosity (same centre and Position Angle (P.A.) of the IUE large aperture). For each subset, we include a figure indicating the precise location of the IUE slit on an optical image of the HHO (typically obtained with a narrow band filter centered at the [S II] lines). Then a table with integrated line fluxes measured on the extracted spectrum is provided. Finally for each IUE image, the extracted spectrum and the resampled image (SILO file) are displayed.

1. A list of general information:

   Name This is assigned according to the Reipurth (1997) Catalogue (hereafter RC).

   Other identifications Other conventional designations provided in the RC.

   Type Indicates to which excitation group the HHO belongs. The abreviations are: HEO and LEO for High and Low excitation Objects, respectively.

Coordinates The JD1950.0 coordinates are provided according to the RC.

Proper motion The proper motion of the nebulosity is provided when available. In general, HH nebulosities have many knots whose proper motions may differ, we have selected a significant knot to provide a rough idea of the velocity of the object in the plane of the sky; we also indicate the reference from which the data have been extracted.

Radial velocity The radial velocity of the object is provided in km/s; the source reference is indicated.

Suspected source The suspected exciting source of the object is provided (from the RC).

Region The star formation region with which the HHO is associated is indicated (from the RC).

Distance The distance to the HHO is provided (from the RC).

Characteristic size The approximate projected size of the nebulosity (in arcsec) is given; this has been determined by us from the optical images used to indicate the location of the IUE slit on the HHO.

Associated with molecular outflow The connection between the HHO and a known molecular outflow is indicated.

P.A. of the jet The P.A. of the jet exciting the nebulosity is provided. This has been taken either from previous works or estimated by us from published data. In both cases the reference containing the data is provided.

2. A list with the IUE observations

   The log of the IUE observations is provided. For each observation we indicate, the camera and image number, the dispersion, the aperture, the date of observation, the integration time and the quality given by the observer according to standard codes adopted for the description of the IUE images. The P.A. of the IUE large slit in the plane of the sky is also indicated.

3. For each set of IUE observations obtained with the same P.A. and centre we provide:

A key map This is a contour (isophotes) map of the nebulosity on top of which we have plotted the IUE Large Aperture (LAP). The contours map has been scanned from the publication indicated at the bottom of the figure; in most objects the images have been obtained with a narrow band filter centered at the optical forbidden lines of [S II] (centered at $\lambda\lambda$ 6717,6731 Å). All the maps in this catalog have the same spatial scale: the field is $\sim 40'' \times 40''$ and the separation between two small tickmarks is $2''$. The lenght of the LAP on the map is $\sim 22''$; in practice, there is a small difference of $\sim 1''$ between the projected size of the LAP in the LWP and SWP cameras. A small mark has been drawn on the border of the aperture to indicate the P.A. (removes the $\pm 180^o$ uncertainty); this information is relevant to interpret the resampled image (see below).

A list with basic data derived from the IUE observations A table with the mean fluxes of the most prominent UV lines (Mg II (UV1), C II]$_{2330}$, C III]$_{1909}$

and C IV (UV1)) is provided. No attempt has been made to measure the strength of the fluorescent H_2 lines which are usually strong in low excitation objects. Neither we have tried to measure the strength of the continuum although it is strong in some sources.

The line fluxes have been measured directly on the extracted spectrum and no special procedures, such as those applied by Cameron & Liseau (1990) or Liseau et al (1996), have been used. Therefore, they only provide an overall idea of the UV spectral characteristics of the objects.

Spectra Two figures are shown per IUE image: the extracted spectrum at the top and the resampled image at the bottom. Only spectra where actual emission has been detected are displayed. The extracted spectrum displayed is the produced by NEWSIPS (SWET extraction procedure); flagged pixels (see the NEWSIPS manual) are marked with asterisks. The resampled image (SILO file) contains all the spatial information since it is *a primary array produced by resampling the photometrically corrected portion of the image using the modified Shepard algorithm taken from the Numerical Algorithms Group (NAG) software package* (see NEWSIPS manual). The gray scale is coded so the larger the flux the darker the gray level. The white points represent the location of the reseau marks. The location of the IUE large and small apertures is clearly seen in the SWP images due to the geocoronal Lyα emission. The coordinate along the y-axis is the distance from the centre of the LAP (in arcsec). We have assigned positive values to increasing distances from the centre towards the P.A. (tickmark on the LAP of the "key map") and negative values to increasing distances from the center towards P.A.$\pm 180^o$.

The spatial structure of the HHOs UV emission is resolved along the LAP for some objects. The spatial resolution of the IUE along the LAP is similar for the LWP and LWR cameras; the best is near 3000 Å and decreases shortwards: at 3000 Å, the spatial resolution is $\sim$ 2.4 pixels (3.″6) and 2.6 pixels (3.″9) in the LWP and LWR cameras respectively, while at 2000 Å the spatial resolution is $\sim$ 3.0 pixels for both cameras. The SWP camera spatial resolution is nearly constant from 1200 to 1400 Å ($\sim$2.7 pixels or 4.″1) and decreases to 3.7 pixels at 1950 Å(see the NEWSIPS manual for more details).

3 List of HHOs observed with the IUE

HH no.	RA(1950.0)			Dec(1950.0)			Suspected source	Region	Type	LW		SWP	Page No.
	h	m	s	°	’	”				P	R		
12	03	25	52.1	+31	09	51	SVS12	NGC1333		1	0	1	17
11	03	25	59.0	+31	05	35	SVS13	NGC1333	LEO	3	0	2	19
7	03	26	02.5	+31	05	10	SVS13	NGC1333	LEO	2	0	1	25
29	04	28	33.2	+18	00	00	L1551 IRS5	L1551	LEO	4	0	8	31
30	04	28	43.6	+18	06	03	HH30 IRS	L1551		1	0	3	47
203	05	32	54.8	-05	26	51		M42		8	0	7	49
204	05	32	55.2	-05	27	06		M42		2	0	3	51
34	05	33	03.7	-06	28	53	HH34 IRS	L1641		1	0	5	53
1	05	33	54.5	-06	46	57	HH1/2 VLA1	L1641	HEO	0	4	10	59
2	05	33	59.7	-06	49	04	HH1/2 VLA1	L1641	HEO	0	4	11	79
43	05	35	45.4	-07	11	04	HH43 IRS1	L1641	LEO	1	0	6	105
24	05	43	36.1	-00	11	02	SSV63	NGC2068		1	0	5	119
46	08	24	17.1	-50	50	34	HH46/47 IRS	Gum Nebula		0	0	3	125
47	08	24	22.8	-50	50	00	HH46/47 IRS	Gum Nebula	LEO	1	0	4	127
57	16	28	56.8	-44	49	17	V346 Nor	Norma 1	LEO	1	0	4	137
216	18	16	05.1	-13	53	03		NGC6611		0	1	1	139
81	18	16	07.5	-20	52	53	IRAS18162-2048	L291		1	0	1	145
32	19	18	07.9	+10	56	21	AS353A	Aquila	HEO	0	1	2	147
168	22	54	04.8	+61	45	59	HW2	Ceph A		0	0	1	153

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