HERBIG-HARO OBJECTS

RECENT OBSERVATIONS OF HERBIG-HARO OBJECTS, OPTICAL JETS, AND THEIR SOURCES

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ABSTRACT. Recent observations of Herbig-Haro objects and optical jets are reviewed, including observations of the stellar objects responsible for these and related outflow phenomena. The review discusses observations obtained in the following wavelength bands: radio, far-infrared, infrared, optical, and ultraviolet.

1. INTRODUCTION

The occurence of energetic mass outflows from all types of young stars and their possible impact on pre-main sequence evolution has only recently become fully appreciated (e.g. Lada 1985). In the case of low-mass stars ($M \lesssim 3\ M_\odot$) these outflows are mostly studied through CO line observations of the so called "high-velocity" molecular gas accelerated by these stars or through optical observations of Herbig-Haro (HH) objects and "optical" jets.

HH objects and "optical" jets are tracing the outflowing matter with the highest velocity and highest degree of collimation (e.g. Schwartz 1983, Mundt 1985a, 1986). Their radial velocities reach values of about 400 km/s and several jets have length-to-diameter ratios of about 20 (Mundt, Brugel, and Bührke 1986). In contrast, the "high-velocity" molecular flows associated with low-mass stars have typical velocities of 5-30 km/s and their length-to-diameter ratio is about 2 to 3 (e.g. Lada 1985). HH objects and "optical" jets (hereafter called jets only) are intimately related phenomena. They show the same emission-line spectrum, which is very probably formed behind shock waves with velocities of 40-100 km/s (e.g. Schwartz 1983; Mundt, Brugel and Bührke 1986). Furthermore, several (often long known) HH-objects form the brightest knots of a jet. On the basis of such observations it has been suggested (e.g. Mundt 1985a,b) that many HH objects simply represent the locations of the most brightest radiative shocks in a jet from a young star. These shocks have to be rather oblique, since the typical shock velocities are considerably lower than the flow velocities of

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about 200-400 km/s (Mundt 1986).

A large and rapidly growing number of papers have been published within the past 5 years on HH objects and other outflow phenomena associated with young stars. There have also been several conferences at which these topics have been discussed. For conference proceedings the reader is referred to Roger and Dewdney (1981), Canto and Mendoza (1983), Black and Matthews (1985), Serra (1985), and Henrikson (1986). For reviews on HH objects, jets, and molecular flows the reader is referred to Schwartz (1983), Mundt (1985a,b), and Lada (1985), respectively. In order to avoid too much overlap with these other reviews, I will concentrate here on the observational results obtained during the past three years on HH objects, optical jets, and on the stars responsible for these outflow phenomena. These observations have been obtained through a variety of methods over a very broad wavelength range (20 cm - 10^{-5} cm). The observations in the various wavelength bands will be discussed in order of decreasing wavelength.

2. VLA RADIO CONTINUUM OBSERVATIONS

2.1. HH1, HH2 and their "central" star

HH1 and HH2 are the only HH objects detected so far with the VLA (Pravdo et al. 1985). In all other cases only the outflow source has been detected. In some of these latter cases, however, part of the radio emission may originate in compact HH-like or jet-like nebulae near the source (see §2.2.).

At 6 cm HH1 and HH2 were detected by Pravdo et al. at a flux level of 0.55±0.04 mJy and 1.22±0.04 mJy, respectively. The observed spectral indices are -0.2±0.3 (HH1) and -0.2±0.1 (HH2) leading Pravdo et al. to conclude that one is observering free-free emission from an optically thin region. The Hα flux measured for these two objects is consistent with this interpretation.

Pravdo et al. (1985) also detected the "central" star of HH1 and HH2 at a flux level of 1.2±0.04 mJy (λ = 6 cm). Its spectral index of +0.4±0.2 is significantly different from HH 1/2 and is consistent with free-free emission from an ionized stellar wind. These VLA observations together with recent CCD observations (Strom et al. 1985, Scarott et al. 1986) showed that this VLA source is the source of the bipolar outflow traced by HH1 and HH2 and not the Cohen-Schwartz star.

2.2. Outflow Sources

The existing VLA data on sources of HH objects and jets are summarized in Table 1. In general these sources are rather weak with fluxes often of the order of 0.1 mJy, even for sources with distances of only 150 pc. It has been pointed out by Bieging, Cohen, and Schwartz (1984) that the liklihood of detecting an outflow source with the VLA is much higher than in the case of a "normal" T Tauri star (TTS). This suggests that the former objects have stronger winds on average. However, the observed spectral indices suggest that only in some objects is the wind

Table 1: Radio Fluxes and Spectral Indices of Jet and HH Object Sources

Source	Peak Flux at 6cm (mJy)	Spectral Index α	Ref.	Source	Peak Flux at 6cm (mJy)	Spectral Index α	Ref.
SSV13	0.27^a	-	1	VLA1-HLTau	0.13	-	2
(HH7-11)				HH34-IRS	0.08^a	-	2
Haro 6-5B	0.15	0.1	2	VLA1-HH1/2	1.2	0.4±0.2	4
(=FS TauB)				HH43-IRS1	0.2^a	-	1
T Tau N	0.7	1	3	HH24-IRS	0.6	-	1
T Tau S	5	0.44	3	HH26-IRS	0.2^a	-	1
DG Tau	0.51	0.55±0.3	1	R Mon	0.4^a	-	5
Haro 6-10	0.8	-	1	AS 353A	0.5^a	-	6
L1551-IRS5	1.7	0.05±0.06	1	1548C27	0.1^a	-	2
HH30-star	0.08	-	2				

a= 2σ upper limit; 1 = Bieging, Cohen, and Schwartz 1984; 2= Brown, Drake, and Mundt 1985, 1986, 3 = Schwartz, Simon, and Campbell 1986; 4 = Pravdo et al. 1985; 5 = Cohen, Bieging, and Schwartz 1982; 6 = Snell and Bally 1986.

observed directly (i.e.$\alpha \approx 0.6$). Instead an optically thin ($\alpha \approx 0$) and relatively compact - but spatially resolved - radio emission region is observed around the star. For example, the radio emission region around L1551-IRS5 and DG Tau is clearly resolved along the jet axis (Bieging, Cohen, and Schwarz 1984) and radio emission regions with sizes of the order of 100 AU have been found around XZ Tau, HL Tau, and Haro 6-5B (Brown, Drake, and Mundt 1985, 1986). These "extended" radio emission regions are probably ionized by shocks in the outflowing matter.

3. CO LINE OBSERVATIONS OF HIGH VELOCITY MOLECULAR GAS NEAR HH OBJECTS

The reader is refered to Edwards and Snell (1984) and references therein for a detailed discussion of this subject. These authors showed that "high-velocity" molecular flows (v=5-30 km/s) are relatively common in molecular clouds with associated HH objects. In total they found 17 anisotropic or bipolar molecular flows in the vicinity of 58 HH objects which are characterized by ^{12}CO full velocity widths $\gtrsim$10 km/s. 75% of the 58 HH objects lie within 10' of the outflow center. However, only 25% of these 58 lie within 1' of the outflow center and are those objects which are more likely to be directly related to the molecular outflow, since "optical" flows have typical length of 0.1 pc (2.5' at 150 pc; Mundt, Brugel, and Bührke 1986).

However, all these numbers are not very meaningful, since for many HH object (e.g. for about 70% in Herbig's 1974 catalogue) the source is not known. In addition, many HH object and jet sources are low-luminosity objects ($L \approx 1\ L_\odot$) and are expected to have weaker and slower outflows requiring sensitive, high-spatial resolution observations in order to be detected. Indeed, about 80% of the molecular flow sources in the list of Edwards and Snell (1984) with known luminosities have $L \lesssim 20\ L_\odot$ and about 30% have $L = 200\text{-}10^4\ L_\odot$. Nevertheless, it is quite an important task to investigate the relationship between "optical" flow phenomena and molecular ones. To find out, for example, whether the molecular flows might be driven by the high-velocity gas traced by HH objects and jets. This requires definite source identifications and in many cases sensitive molecular line observations at high spatial resolution.

Mundt, Brugel, and Bührke (1986) have estimated the mass fluxes of 16 jets and other highly collimated flows emanating from low luminosity stars (0.1-100 $L_\odot$) and investigated whether these jets could drive the molecular flows of these young stellar objects. They concluded that momentum driven molecular flows are very unlikely, since the momentum fluxes of the jets are typically 100 times smaller than those of the molecular flows associated with low-luminosity stars. Energy driven molecular flows, however, would be consistent with the currently available data.

4. IR AND FIR OBSERVATIONS OF JET AND HH OBJECT SOURCES

A relatively large number of IR (1-20 µ) and in particular FIR (20-160 µ) observations have been carried out in recent years. In the latter wavelength region very little data predate 1983 (for details see Schwartz 1983). Relevant recent publications in the IR and FIR are: Cohen and Schwartz (1983); Cohen, Harvey, and Schwartz (1985, and references therein); Vrba, Rydgren, and Zak (1985); Harvey et al. (1986). The FIR observations discussed by these authors have all been carried out with the help of NASA's Kuiper Airborne Observatory. So far relatively few FIR observations of these objects based on IRAS data have been published (Emerson et al. 1984; Clark and Laureijs 1986). Polarimetric observations, at IR and optical wavelengths, of these and related objects have been discussed by Hodapp (1984). All of these new observations together with the data obtained before 1983 (see Schwartz 1983) are important for the identification of sources, for measuring their spectral energy distribution and bolometric luminosities, and for determining the spatial distribution of their circumstellar dust.

From the existing data it is evident that these sources are in general much more obscured than "normal" TTS. For the latter stars A_V is typically 0.5-3 (Cohen and Kuhi 1979), while A_V values of 10-20 are not unusual for the jet and HH object sources. This strongly indicates that the outflow sources are younger than "normal" TTS. Nevertheless, most sources have optical counterparts on deep CCD images taken in the 0.6-1 µ region. The CCD images also show that many sources are associated with (cometary) reflection nebulae. Their spectral energy distributions are also quite different compared with those of "normal" TTS. For the sources with known K-L colors (≈ 20) the average K-L value is 2.0, while the corresponding value for the TTS in the

Taurus-Auriga dark cloud is 0.8 (Cohen and Kuhi 1979). On average, about 70% of the source energy is radiated at wavelength larger than 20 μ. The corresponding value for the TTS in Taurus-Auriga, which are not outflow sources (like DG Tau or T Tau), is 10-20% (Rucinski 1985). The FIR energy distribution of the sources is typical of cool dust grains with T = 40-60 K.

In about 30 cases, the probable source of flow (traced by HH objects and jets) has been identified by various means. For about 20 sources FIR measurements have been carried out. However, only for about two-thirds of these there is no obvious confusion problem with other sources in the beam. The bolometric luminosities derived from the FIR data for 22 objects (the confusion problem is neglected here) have the following distribution: 50% have $\lesssim 20\ L_\odot$, 30% have 20-100 $L_\odot$ and 20% have about 10^3-$10^4\ L_\odot$. The latter sources are R Mon, LKHα 234, GGD 37/Cep A (e.g. Lenzen, Hodapp, and Solf 1984), and IRC2-M42 (Jones and Walker 1985; Taylor et al. 1986). In the latter 3 cases there are seveve source confusion problems. Nevertheless, it obvious that about 80% of the known sources are low-luminosity (low-mass) stars with $L \lesssim 100\ L_\odot$.

5. H_2 LINE OBSERVATIONS

Since the first extensive observations of HH objects in the IR H_2 lines by Elias (1980) many more HH objects have been observed and several flows have been mapped. Table 2 gives an overview of the objects which have been detected and which have been mapped. For the latter cases, a beam size is given. These maps have been in general obtained in the $\nu = 1 - 0$ S(1) line at 2.12 μm.

Table 2: HH Objects detected in the IR H_2 lines

Object	beam size of map (arcsec)	Ref.	Object	beam size of map (arcsec)	Ref.
HH12	15	1	HH19	-	5
HH7-11	12, 19.6	2, 3	HH46	-	6
HH6	15	1, 3	HH52	5	8
HH5	-	3	HH53	5	6, 8
T Tau/ Burnham's Neb.)	-	4, 5	HH54	5	6, 8
HH40	-	6	HH101	-	9
HH1/2	7.5	6, 7	HH32	5	8, 10

References: 1 = Lane and Bally 1986; 2 = Zealey, Williams, and Sandell 1984; 3 = Lightfoot and Glencross 1986; 4 = Beckwith et al. 1978; 5 = Zinnecker et al. 1985; 6 = Elias 1980; 7 = Harvey et al. 1986; 8 = Zealey et al. 1984; 9 = Brown et al. 1983; 10 = Zealey et al. 1985

A comparison of the H_2 maps with the optical images shows that the H_2 emission occurs in the same general area as the optical emission and its intensity is correlated with the optical intensity. This is consistent with the detection of HH19 and HH12, but not of their associated jets. In a few cases, there are significant differences. One example is HH2 where the peak of the H_2 emission is 7" NW of the brightest optical knot (Harvey et al. 1986) However, a detailed comparison is often hampered by the large beam sizes used for the H_2 observations.

From the existing data very little is known on the structure of the shocks generating the H_2 emission or the dynamics of the pre- and post-shock gas. For example, are we observing molecular gas entrained in high-velocity jets? Alternatively, is the emission produced by shocks, formed as a result of the high velocity flow ploughing into the ambient molecular matter (e.g. at the jet's working surface)? To answer these questions radial velocity measurements and mapping at higher spatial resolution are needed. Such observations would be very interesting for those HH objects where a significant fraction of the optical emission is apparently formed in a bow shock(see § 6.2.2. and Mundt, Brugel, and Bührke 1986). In these cases the H_2 emission should be generated in the wings of the bow shock (where the normal shock velocity is low) and the optical emission near the apex.

6. OPTICAL OBSERVATIONS

6.1. Proper Motion Measurements

Since the discovery of large proper motions for HH28 and HH29 by Cudworth and Herbig (1979) the proper motions of 66 HH knots have been measured (see Schwartz, Jones, and Sirk 1984, and references therein). These 66 knots are associated with about 25 outflows. A histogram showing the frequency distribution of tangential velocities of 63 HH knots has been published by Schwartz (1986). In this histogram most HH knots have small proper motions and the number of HH knots in each velocity bin is approximately decreasing monotonically with increasing tangential velocities. The highest measured tangential velocity (350 km/s for HH1, Herbig and Jones 1981) is nearly as high as the highest radial velocity reported for an HH object (410 km/s for HH32, Hartigan, Mundt, and Stocke 1986). It has to be emphasized, however, that the tangential velocities with nominal values $\lesssim$100 km/s are very unreliable. About 65% of these values have errors larger than about 50%.

For most of the relatively faint knots in the jets recently discovered through CCD imaging no proper motion data are available. The existing data on the bright knots in these jets show that not only the knots at the jet's end are moving (like HH47A), but also some of the knots along the jet (e.g. HH11). This suggest, that at least some of these flows are not in steady state conditions, where only the knots at the jet's end (the working surface) should be moving.

6.2. CCD Imaging

CCD detectors have been frequently used in recent years to study high velocity outflows through their shock induced optical line emission. These studies have led to the discovery of jets (e.g. Mundt and Fried 1983; Strom, Strom, and Stocke 1983; Mundt et al. 1984; Mundt, Brugel, and Bührke 1986; Krautter 1986; Ray 1986) and new HH objects and related nebulae (e.g. Strom et al. 1986). Furthermore, imaging in HH emission lines and in the continuum have helped to distinguish between scattered light and in situ formed shock emission in complex nebulae. These latter studies have been supplemented in several cases by CCD imaging polarimetry (e.g. Lenzen 1986, Scarott et al. 1986)

6.2.1 Optical Jets. More than 20 jets are known today. Their typical observational properties are summarized in Table 3. For a recent detailed discussion of the existing observational data the reader is refered to Mundt, Brugel, and Bührke 1986 (see also Mundt 1985a, 1985b, 1986). Morphologically, the jets are seen as radially projected single or bipolar elongations with an observed aspect ratio (length to width) of typically 10-20. In high dynamic range images all jets show knots. In four cases a series of 4-6 roughly equidistant knots is observed.

Table 3: Typical Observational Properties of the Jets

projected length:	0.02 - 0.5 pc
length-to-width ratio:	10 - 20
opening angle:	3 - 10°
radial velocity:	$\lesssim$400 km/s
tangential motion of knots:	$\lesssim$300 km/s
collimation length:	3 x 10^{-3} pc
electron density:	500 - 2000 cm^{-3}
spectrum:	shock-excited emission line spectrum with v_{shock} = 40-100 km/s
sources:	T Tauri-like stars with $L \approx 1-10\ L_{\odot}$

The brightest knots in these jets are often known as HH objects and have been discovered many years before their associated jet. In about 60% of all jets, a bright knot, or knotty region, is observed at the (presumable) end of the jet. These bright knots or knotty regions have been interpreted as the working surface of the jet (Mundt 1985b, Dyson 1987), i.e. as that region, where the jet is colliding with the ambient medium. This interpretation is strongly supported by the radial velocity decrease observed in these knots (see § 6.3.) and the bow shock structures associated with them (see § 6.2.2.). The knots along the jet have been interpreted as internal shocks, which - in principal - can be excited through various mechanisms. One mechanism, pressure gradients in the external gas, seems to be relatively important in this respect (Mundt, Brugel, and Bührke 1986; Falle, Innes, and Wilson 1986).

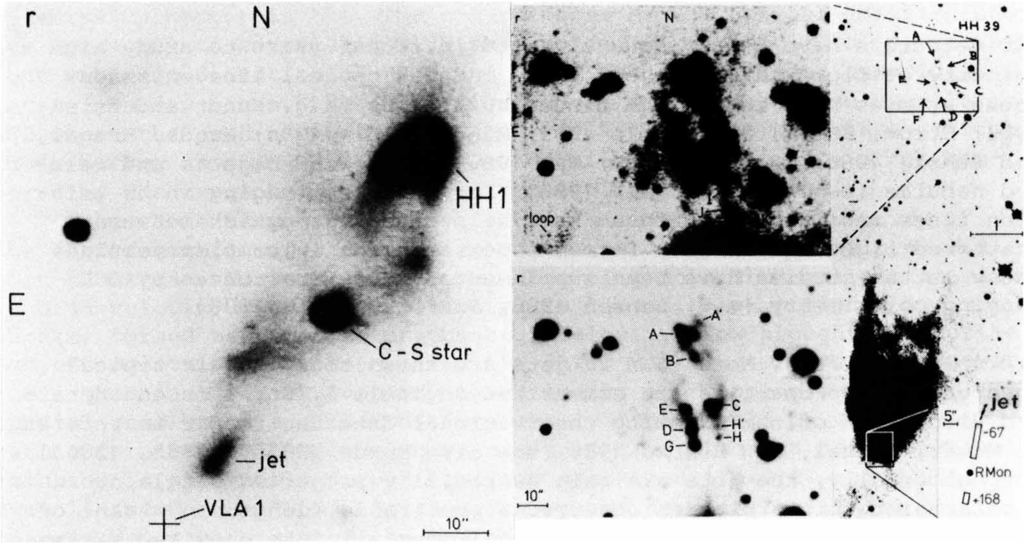

Fig. 1: CCD images of HH1 and HH39 illustrating their bow shock like structures.

As mentioned above, many jet sources are associated with cometary (or cone-like) reflection nebulae. In all these cases the jet axis is lying approximately parallel to the nebular axis (e.g. Mundt, Brugel, Bührke 1986). It is not yet clear how this very interesting morphological association is to be interpreted. In several cases, spectroscopy of these reflection nebula has allowed a study of the often highly obscured jet source. For example, it was shown by this method that L1551-IRS5 probably belongs to the rare class of FU Orionis objects (Mundt et al. 1985).

6.2.2. Bow Shock Structures. Recent CCD imaging has shown that HH1, HH39, and in particular HH34 show bow shock like structures (Reipurth et al. 1986; Mundt, Brugel, and Bührke 1986). CCD images of HH1 and HH39 are reproduced in Fig. 1. For an Hα image of HH34 see paper by Bührke and Mundt in this volume. All three objects have the following properties in common:

1. The convex side of the bow shock structure points away from the jet source.
2. They are internally highly structured (i.e. knotty and patchy). This suggest that the knots in these HH objects are not isolated entities but part of one large-scale flow pattern.
3. A relatively short jet is pointing from the source towards all three HH objects. This jet can't be traced all the way to the HH object.

The observed structures have been interpreted as a bow shock, created by the rapid propagation ($v \gtrsim 100$-200 km/s) of the jet's working surface through the ambient gas (Mundt, Brugel, Bührke 1986). This interpretation is consistent with the large proper motions of HH1 and HH39 and the radial velocities of HH34. The large spatial extend of the bow shocks can probably be explained by the partial ionization of the pre-shock gas (Raga 1986).

6.3. Long-Slit Spectroscopy

HH objects and jets show in general a complex spatial structure in velocity, velocity dispersion, electron density and line excitation. Often strong gradients are observed, which in several cases can't be properly resolved by ground based observations. Long-slit spectroscopy is therefore one of the most powerful methods to study these flows (in particular when one deals with one-dimensional structures). High quality long-slit spectra with a velocity resolution of 15-100 km/s have recently been obtained of the following flows: GGD37 (Lenzen, Hodapp, and Solf 1986), HH7-11 (Böhm and Solf 1986), T Tau/HH1555 (Bührke, Brugel, and Mundt 1986), L1551-IRS5, HH28/29 (Sarcander, Neckel, and Elsässer 1985; Stocke et al. 1986), HH34 (Reipurth et al. 1986; Bührke and Mundt 1987), HH1/2 (Böhm and Solf 1985), HH24 (Solf 1987), R Mon/HH39 (Brugel, Mundt, and Bührke 1984; Walsh and Malin 1985), HH46/47 (Graham and Elias 1983; Meaburn and Dyson 1986), Th-28 (Krautter 1986), HH32 (Hartigan, Mundt, and Stocke 1986; Solf, Böhm, and Raga 1986), Haro 6-5B, DG Tau, DG TauB, HH30, VLA1-HL Tau, HH33/40, HH19, 1548C27 (Mundt, Brugel, and Bührke 1986).

In the case of jets and other highly collimated flows traced by HH objects, the following correlations and trends have been derived from the currently available data by Mundt, Brugel, and Bührke (1986):

1. In 9 out of 12 flows with reasonable [SII] $\lambda\lambda$ 6716, 6731 data the electron density is decreasing with increasing distance from the source (or at least more distant regions have a smaller average electron density). This correletation has been interpretet by a flow of approximately constant mass flux of which the cross section is increasing with increasing distance from the source.
2. *All* jets which show a bright knot at their end, *and* which have sufficiently high radial velocities ($\gtrsim$100 km/s) to do detailed kinematical studies, show a decrease in radial velocity within (or near) the knot. These knots are interpreted as the jet's working surface. The observed radial velocity decrease is due to momentum exchange with the external gas and due to dissipation of part of the jet's kinetic energy in the shocks of the working surface.
3. There is no indication that the radial velocities are in general decreasing along the flow channel, even if several knots (i.e. internal shocks) are present. This suggests that the kinetic energy is in general transported relatively efficiently along the jets. This is also expected on theoretical grounds, if the flow velocities are higher than about 200 km/s.

The long slit data of HH1, HH32, and HH34 have been discussed extensively in the context of bow shock models of HH objects (e.g. Solf, Böhm, and Raga 1986). As discussed in § 6.2.2. only for HH1 and HH34 CCD imaging suggests that at least part of the emission originates in a bow shock. The long-slit spectra of HH1 show that the velocity dispersion is highest near the apex of the presumed bow shock structure and decreases towards the central source. This correlation is in (qualitative) agreement with simple bow shock models (e.g. Raga 1986 and references therein).

7. IUE OBSERVATIONS

HH objects have been observed extensively in the UV spectral range with the IUE satellite, which went into operation more than eight years ago. IUE observations showed that HH objects have a surprisingly strong continuum in the UV. Two-photon emission of hydrogen has been suggested as a likely source of that continuum. Furthermore, the studied HH objects can be divided into low- and high-excitation objects. The former group shows only H_2 fluorescence lines in the short wavelength range IUE spectra, while in the latter ones these lines are not observed but instead emission from CIV, CIII, SiIV or OIII is seen. For more details, the reader is refered to the reviews of Böhm (1983) and Schwartz (1983).

Strong variations in the CIV 1550 and CIII 1909 line of HH1 have recently been reported by Brugel et al. (1985). The IUE data indicate a monotonic decrease in the fluxes of these lines by a factor of at least 4-6 between 1979 and 1983. Surprisingly, no indications of drastic changes in the optical range (specifically in the [OIII] 5007 line) have been found.

Using 12 and 14 hour exposures in the short wavelength range of IUE Böhm et al. (1986) have obtained new spectra of HH1 and HH2 with a relatively high signal-to-noise ratio. The continua of both objects peak at about 1575 Å and not near 1410 Å, where the two-photon continuum of hydrogen has its maximum. The wavelength dependence of that continuum suggests that significant parts of it are due to H_2 continuum emission. The data obtained by these authors also showed that the contribution of the "Orion Reflection Nebulosity" to the continuum emission of these objects in the 1300-1900 Å wavelength range is not higher than 20-30%. (see also Mundt and Witt 1983).

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