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Final Technical Report
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The research supported by this grant was mainly concerned with the observation, data reduction and interpretation of ultraviolet spectra (obtained with the International Ultraviolet Explorer) of Herbig-Haro objects, stellar jets and (in a few cases) reflection nebulae in star-forming regions. Intermediate results have been reported in the required semi-annual reports.

The observations for this research were obtained in 23 (US1) IUE shifts. The spectra were taken in the low resolution mode with the large aperture. The following topics have been investigated:

1. Detection of UV spectra of high excitation Herbig-Haro (HH) objects, identification of emission lines, and a preliminary study of the energy distribution of the ultraviolet continuum;
2. Details of the continuum energy distribution of these spectra and their possible interpretation;
3. The properties of the reddening (extinction) of HH objects;
4. The possible time variation of strong emission lines in high excitation HH objects;
5. The ultraviolet emission of low excitation HH objects, especially in the fluorescent lines of the H₂ molecule;
6. The ultraviolet emission in the peculiar object HH24;
7. The spatial emission distribution of different lines and different parts of the continuum in different HH objects;
8. Some properties of reflection nebula, in the environment of Herbig-Haro objects.

We shall now discuss each topic in somewhat greater detail.

1. UV Spectra of High Excitation HH Objects, Line Identification and Continuum Study.

Herbig-Haro objects are shock excited regions which are, in most cases, generated by the jet outflows from young stars. They give us some insight into the physics of the circumstellar matter in star forming regions. Typical shock velocities of “high excitation” HH objects lie in the range of 80-150 kms^{-1} (and possibly higher). Although one would expect fairly strong ultraviolet emission under these conditions, the relatively easy detection of HH objects with IUE was nevertheless a surprise because these objects are faint in the optical and fairly strong interstellar extinction was to be expected.

In 1980, 1981, and 1982 we obtained a number of spectra of the relatively bright objects HH1 and HH2 in the SWP and LWR range. The SWP range of HH1 had been studied already slightly earlier (but at that time unknown to us) by Ortolani and d’Odorico (A & A, 83, LS, 1980). We did obtain, however, the first LWR spectrum of HH1 and the first SWP and LWR spectra of HH2. We detected *e.g.*, moderate to strong emission lines of CII 1335, SiIV 1394, 1403, CIV 1548, 1551, SiII] 1808, 1817, SiIII] 1883, 1892, CII] 2326 and MgII 2796, 2803 in both objects (Böhm *et al.* 1981; Böhm-Vitense *et al.* 1982*). The most interesting aspect of the continuum seemed to be the steep rise towards shorter wavelengths. The study of ultraviolet spectra of HH objects added very important constraints to the shock models of HH objects. Combining the results from optical observations with IUE data (*e.g.*, Böhm 1983) it became clear that the spectra are more convincingly explained by emission from bow shocks (Hartmann and Raymond 1984, ApJ, 276, 560).

2. Details of the Continuous Energy Distribution.

The spectra described in Chapter 1 were all based on 3-6 hours exposures and were typically somewhat faint. In order to improve the accuracy of the photometry of the fainter emission lines and to improve the accuracy of the determination of the continuum energy

* References which quote only the authors’ names and the year of publication refer to our own IUE papers which are listed at the end of this report.

distribution we began in 1985 to obtain two-shift exposures of the SWP spectra of a number of Herbig-Haro objects. This research, which used in the usual way the ESA-SERC and the following US1 shift, was first carried out jointly with Dr. Reinhard Mundt and Dr. T. Bührke of the Max-Planck-Institut für Astronomie in Heidelberg and since 1988 with Dr. Josef Solf (also of the MPI in Heidelberg). These investigations permitted us not only to improve the spectrophotometry of emission lines and the continuum but also gave us an opportunity to study the spatial distribution of the emission in different lines and different wavelength intervals of the continuum (using line-by-line spectra) and to find possible time variations (see below).

We shall now briefly discuss the more detailed investigations of the energy distribution of the continuum. It had been suggested (Dopita, Binette and Schwartz 1982, ApJ, 261, 183; Brugel, Shull and Seab 1982, ApJ, 262, L35) that the continuum in HH objects is a collisionally enhanced 2-photon continuum of hydrogen. If this is true then we should have in F_λ (flux per unit wavelength) a monotonic increase towards shorter wavelengths to $\lambda \sim 1410 \text{ \AA}$ and from there a steep decline towards the wavelength of Lyman α ($\sim 1216 \text{ \AA}$). Shortward of $\sim 1400 \text{ \AA}$ there are many sources of uncertainties (*e.g.*, overlapping faint unidentified emission lines) so that the confirmation of a maximum near 1410 \AA still has not been possible with certainty. We did, however, find an additional continuum contribution between 1400 and 1600 \AA with a maximum near 1580 \AA (Böhm *et al.* 1987). This additional continuum was tentatively identified with the fluorescent H_2 continuum first described by Dalgarno, Herzberg and Stephens (1970, ApJ, 162, L49). If this assumption is correct this continuum gives us information about the destruction rate of H_2 molecules in HH objects.

We have also studied the ultraviolet energy distribution of the continuum in a number of other Herbig-Haro objects using also 2-shift exposures. Results are now available for HH1, HH2H + HH2A', HH2G, HH43 and HH47 (see also Böhm *et al.* 1991; Böhm, Noriega-Crespo and Solf 1993). In all these objects the continuum energy distributions are surprisingly

similar and the fluorescent H_2 continuum seems to be present. The final clarification of this problem will require spectra of HH objects with much higher spectral resolution.

3. Reddening of Herbig-Haro Objects.

Since Herbig-Haro objects are usually visible in the outer regions of molecular clouds the determination of their reddening and their interstellar circumstellar extinction is important. This is especially true if IUE and optical data are compared. If the shape of the reddening curve is known (or assumed to be known) we have usually determined the $E(B-V)$ from the Miller method (1968, ApJ, 154, L57) which makes use of the ratio of the near infrared (*e.g.*, 10318 Å) to the blue (*e.g.*, 4068 Å) lines of [SII] which originate from the same upper level (see *e.g.*, Solf, Böhm and Raga 1988, ApJ, 334, 229). A more difficult problem is the determination of the shape of the reddening curves in the star forming regions in which HH objects are observed.

From circumstantial evidence we argued some time ago (Böhm and Böhm-Vitense 1984) that the shape of the extinction curve appropriate for *e.g.*, HH1 and HH2 should be close to the so-called θ Orionis curve (which has $R \sim 5.4$, see Bohlin and Savage 1981, ApJ, 249, 109). More recently (Böhm, Raga and Binette 1991) we have tried to determine the shape of reddening curve for HH1 and HH2 in a more systematic way. We have determined the reddening curve from a comparison of IUE as well as optical spectrophotometric data to detailed predictions for bow shock models. To our own surprise we found that the (so-called) “average galactic” extinction curve (with $R \sim 3.1$) leads to much better agreement for HH1 and HH2 than the θ Orionis curve. We feel that this result mainly shows that the problem of the reddening correction of HH spectra (at least if IUE data have to be compared to optical data) has not yet been solved in a satisfactory way.

4. The Possible Time Variation of Strong Ultraviolet Emission Lines in HH Objects.

Optical observations have shown already in the 1950’s that some HH objects are variable. Time-dependent bow shock calculations (*e.g.*, Raga and Böhm 1987, ApJ, 323, 193) show

that under appropriate conditions instabilities can develop with a time scale of 10-20 years. Consequently, it is appropriate to search for variations in the ultraviolet spectra of HH objects. Since the relatively best spectrophotometric data can be obtained for the two strongest emission lines CIV 1550 and CIII] 1909 we looked especially for possible variations in these lines. We found a surprisingly large variation of these lines during the time interval 1981-1984 (Brugel *et al.* 1985). More recently we have been studying time variations for the interval 1979-1991 in HH1 and for the interval 1980-1991 in HH2 (Böhm, Noriega-Crespo and Solf 1992). Apart from the fast 1981-1984 variation in HH1 the variations are usually either moderately slow ($\sim 40\%$ in ten years) or, if fast, they are connected to known optical phenomena. A rapid increase of CIV 1550 in 1981/1982 in HH2 seems, for instance, to be connected with the rapid brightening of the high excitation “knot” HH2A' (see also the discussion of this condensation by Herbig and Jones 1981, AJ, 86, 1232).

5. Ultraviolet Spectra of Low Excitation HH Objects

In the optical range we see a practically continuous range of HH objects of different excitation. High excitation objects show moderately strong [OIII], [SIII], moderately strong [SII] and [OI] and faint [NI] lines. Low excitation objects show no [OIII], [SIII], but extremely strong [SII] and [OI] and strong [NI] lines. Many kinds of intermediate objects exist. In the 5 HH objects for which emission lines have been detected in the SWP range of the IUE we see only extreme cases. Three of them (HH1, HH2, HH32) show high excitation character with CIV 1550 and CIII] 1909 being by far the strongest lines. The two low excitation objects HH43 and HH47 both show an entirely different SWP spectrum. In these the fluorescent H₂ lines 1431, 1446, 1490, 1505, 1547 and 1562 Å are the strongest lines (Schwartz 1983, ApJ, 268, L87). These lines are pumped by Ly α of atomic hydrogen. The H₂ molecule has to be in an excited state ~ 1 eV above the ground level. It is clear that very special physical conditions are required in order to get the fluorescent emission of these lines. In order to get more information about these objects and their physical structure we have attempted to determine the spatial distribution of their emission. Together with Josef Solf of the Max-

Planck-Institut für Astronomie in Heidelberg we obtained 2-shift exposures of SWP spectra of both HH43 and HH47. We studied their “line-by-line” spectra in order to determine the spatial emission distribution (at least in one dimension) of the fluorescent H₂ emission. We found that the emission distribution of the H₂ lines in both objects is indistinguishable from the point-spread function of IUE. That means that the “true” emission distribution is certainly smaller and may be much smaller than the point-spread function of IUE ($\sim 4.''5$) for the appropriate wavelength.

6. The Ultraviolet Emission of HH24A

This is an unusual HH object. Its optical continuum shows high linear polarization (Strom, Strom and Kinman 1974, ApJ, 191, L93; Schmidt and Miller 1979, ApJ, 234, L191) and it is suspected to show dust-scattered light which originally comes from a nearby young stellar object. If this is true one would expect that the ultraviolet spectrum would look like that of a T Tauri star or a Herbig Ae star. In order to check this prediction we obtained (again jointly with Josef Solf of MPI Heidelberg) two 2-shift exposures of HH24A. In order to increase the signal-to-noise ratio of the rather faint spectrum we co-added this spectrum and two moderately long exposures of the SWP spectrum of HH24A obtained earlier by Edward Brugel of the University of Colorado. The result (Böhm, Noriega-Crespo, Solf and Brugel 1992) shows neither the emission-line spectrum of a typical HH object, nor the typical emission line spectrum of an active T Tauri star. It shows no indication of known emission lines but a structured continuum or quasi-continuum which looks somewhat similar to those found in other very faint HH objects like *e.g.*, HH7 and HH11 (Cameron and Liseau 1990, A & A, 240, 409). Possibly these spectra are too faint to permit quantitatively reliable results. We find that very drastic smoothing of the data leads to a “continuum” which may be approximately explained by a 2-photon continuum.

7. The Spatial Emission Distribution in Herbig-Haro Objects

A part of the relevant results for this chapter have already been discussed in Chapter

5 where we presented results on low excitation HH objects. As discussed there we found that the emission regions for the fluorescent H_2 lines are definitely narrower than the point-spread function. They are also considerably narrower than the emission distribution of the continuum in the SWP range and the emission distribution of some strong optical lines like [SII] 6716/6731.

In the high excitation objects HH1 and HH2 we have studied the spatial distribution of the emission of the lines CIV 1550, CIII] 1909, SiIII] 1883/1892 and of the continuum (Böhm, Noriega-Crespo and Solf 1992). It is interesting that in HH2 all lines show a maximum emission at each of the high excitation condensations HH2H and HH2A' with a minimum of the emission in between. (The two condensations are $\sim 4.''5$ apart.) The continuum emission however, shows one broad maximum covering both condensations. This indicates that the continuum emission mechanism is less temperature and/or density sensitive than the line emission mechanism. We also found that the condensation HH2G can be separated well from HH2H and HH2A' in IUE observations. HH2G also shows enough ionization to emit strongly in the CIV 1550 line.

Earlier we have studied the spatial distribution of line emission in a number of HH objects using archival data (Lee *et al.* 1988).

8. The Reflection Nebula NGC 1999

Only loosely connected with the above described IUE studies of Herbig-Haro objects and jets is the study of NGC 1999 which we carried out earlier (Cardelli and Böhm 1984). In connection with the difficult determination of the reddening in spectra of HH objects (see above chapter 3) we were interested in obtaining more information about dust grains in regions close to HH1. (V380 Orionis, the central star of NGC 1999 lies about $2'$ from HH1.) Using IUE spectra of NGC 1999 centered about $15''$ east of V380 Orionis and on V380 Orionis itself we determined the ratio of nebular intensity to stellar flux in the ultraviolet and compared the results to those for other reflection nebulae. We found considerable similarity

to the properties of NGC 7023 which also lies in a star-forming region.

We also used our data (and some model calculations) in order to determine the ultraviolet extinction curve for V380 Orionis. This curve showed that (not completely unexpected) the $\lambda 2200$ feature is unusually weak.

Publications NASA (IUE) Grant NAG5-45
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