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HERBIG-HARO OBJECTS: AN OVERVIEW

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ABSTRACT. The history surrounding the discovery of Herbig-Haro objects and their early interpretation is briefly discussed. Evidence which gave rise to both the reflection and emission hypotheses for their origin is reviewed, and observations which resolved the issue and pointed to the shock wave origin of the objects are summarized. Several theoretical scenarios are reviewed, including the shocked cloudlet, interstellar bullet, and focused stellar wind models. Selected observational highlights on Herbig-Haro objects in the infrared, radio, optical, and ultraviolet portions of the spectrum are discussed. The evidence implicates the Herbig-Haro nebulae with supersonic, bipolar mass outflows from T Tauri stars. Special emphasis is given to recent optical and ultraviolet work which suggests that the blue-ultraviolet continuum in the objects originates from the two-photon process, and new ultraviolet observations revealing H_2 fluorescence emission in low-excitation nebulae are reported.

I. A HISTORICAL PERSPECTIVE

The prototypical Herbig-Haro (H-H) objects were discovered independently by Herbig (1951, 1952) and Haro (1950, 1952, 1953) near NGC 1999 in Orion. The objects (Herbig 1, 2, 3 = Haro 11a, 10a, 12a = H-H 1, 2, 3 as first designated by Ambartsumian (1954)) consist of tightly grouped, semi-stellar knots which are dominated by low-excitation nebular emission lines. The location of the H-H objects in a dark cloud region in the vicinity of Orion population stars implicated the objects with processes of star formation (Herbig 1951, 1957; Ambartsumian 1954). In fact, similar nebular emission was known to be associated with some T Tauri variables, most notably T Tauri itself. In retrospect, perhaps one could credit S. W. Burnham with discovering the first nebula with H-H properties. Using the Lick 36 inch telescope, Burnham (1890) visually detected a faint but distinct nebula extending 4.4" to the southeast of T Tauri which at the time was near minimum light ($m \sim 13.5$), and E. E. Barnard confirmed the detection within a few days. Later, Barnard (1895) reported that the nebula had faded to an indistinct glow, perhaps the first indication of variability in such objects, although it may have appeared less distinct because T Tauri had brightened. As reported by Burnham (1894), Keeler's visual spectroscopic observations of the nebula revealed an emission line (probably Hβ, see Herbig 1950), thus indicating that the nebula probably had an emission origin.

Motivated by these early observations and by photographs of T Tauri obtained by Baade (1945) which exhibited an additional southward nebular protuberance from the star, Herbig (1950) carried out a spectrographic investigation of Burnham's nebula. Emission lines of [O II], [S II], and H, clearly of non-stellar origin, were detected in the extended nebula. The similarity of the spectrum of Burnham's nebula to the spectra of H-H 1 and 2 led to the reasonable assumption that the H-H objects must contain stars. Herbig (1951) suggested that the exciting stars could be either sub-luminous hot stars, or late K or M dwarfs. In view of the T Tauri nebula, Herbig expressed a preference for the latter alternative, suggesting that the semi-stellar knots in H-H 1 and 2 represented late-type stars in an earlier evolutionary phase than T Tauri (Herbig 1951, 1957).

Haro (1952) obtained deep 1-N plates of H-H 1 - 3, finding no evidence for the existence of faint red stars to a photographic limit of $m < 19$ for G or later type stars. Herbig (1951) had suggested that the very faint continuum in H-H 1 would be consistent with the presence of a dwarf star about 5 absolute mags fainter than T Tauri (i.e., $m \sim 16$ at the distance of H-H 1). The continuum was too faint, however, to permit a determination of its probable origin. Böhm's (1956) spectrographic analysis of H-H 1 revealed that a hot (29,000 K) star with 500 $L_\odot$ would be required to produce the nebula by photoionization. This would yield a star of (unobscured) $m \sim 6.5$ at the distance of the Orion complex. The absence of visually detectable stars at the H-H sites thus ushered in the long-standing enigma of the excitation source for the H-H nebulae. We hasten to note that these studies unfolded long before the idea of circumstellar obscuration became fashionable. Even if the picture of a circumstellar dust shell absorbing visible light and re-emitting it as "excess" infrared radiation had been established at the time, it would have been difficult to explain how the (relatively unobscured) nebulae could be produced exterior to such a shell, especially if photoionization were the ionizing mechanism.

Several suggestions were advanced to deal with the question of the energy source for the H-H nebulae in view of the apparent absence of any luminous exciting stars. These suggestions implicitly assumed that the energy sources were located at the sites of the H-H knots, and that some type of proto-stellar activity was at work. Herbig (1951) pointed out that infall of material to a proto-stellar object could produce sufficient energy to excite the nebula, although Böhm (1956) later concluded that accretion heating probably could not produce the ionizing radiation required to generate H-H 1. Osterbrock (1958) suggested that mass outflow from a young star could produce the state of partial ionization indicative of the H-H nebulae. Magnan and Schatzmann (1965) proposed that the nebulae could be produced by an energetic (100 Mev) flow of protons into neutral gas. However, throughout the first two decades of research on H-H objects, no evidence surfaced to confirm the presence of stellar or protostellar objects within the H-H condensations.

The observations of H-H objects experienced a hiatus in the 1960's, the main exception being that of Herbig's (1969) photographic monitoring of H-H 1 and 2 in which light variations of 2-3 mag on a timescale of 5-10 years were detected in the individual knots. A detailed spectrographic study of H-H 1 by Böhm et al. (1973) was the prelude to a flurry of observational and theoretical work which persists to the present time. This overview of research on H-H objects will necessarily be somewhat limited in scope. The reader is referred to recent and more complete reviews of the topic by Böhm (1979), Gyulbudaghian (1980), Cantó (1981), and Schwartz (1983b).

II. THE REFLECTION-EMISSION DEBATE

A pivotal study in the interpretation of H-H objects occurred with the infrared observations of H-H 100 in the Corona Austrina complex by Strom, Strom, and Grasdalen (1974). A visually obscured IR source with an IR energy distribution similar to T Tauri was found to be displaced spatially from the location of the H-H nebula, with the nebula itself exhibiting no detectable infrared emission. A subsequent study by Strom, Grasdalen, and Strom (1974) found similar infrared sources to be associated with H-H 12, H-H 7-11, and H-H 24 (M 78 H-H), in each case clearly displaced from the sites of the nebular knots, but close enough (5"-1') to suggest an association.

A broadband polarimetric study of the condensations in H-H 24 by Strom, Strom, and Kinman (1974) revealed relatively high (~ 15%) optical polarization. The electric vectors from the knots pointed to a common origin which appeared to be coincident with the HH 24 IR source. A model was advanced in which the H-H objects are produced by circumstellar emission which escapes through tunnels in the circumstellar dust shell of a young star, reflecting from dust condensations far-removed from the star (Strom, Grasdalen, and Strom 1974). This interpretation experienced some difficulties as a general explanation for H-H objects. First, most other H-H objects failed to exhibit significant polarization. In addition, a tightly grouped set of H-H condensations would be expected to have identical spectra if produced by reflection from a common source, but the knots of H-H 2 were found to differ significantly from one another (Böhm et al. 1976). Finally, the spectra of the H-H nebulae are typical of low density gas ($n_e \lesssim 10^4$ cm^{-3}) which would not be expected to dominate the light from circumstellar emission.

A different interpretation of the H-H objects was suggested by Schwartz (1975) who carried out a detailed spectrographic analysis of the nebulae associated with T Tauri. In addition to confirming the H-H-like character of Burnham's nebula, a new H-H nebula detached from T Tauri was discovered at the eastern rim of Hind's nebula, a reflection nebula located about 45" west of T Tauri. Hind's nebula was found to be produced by reflection from T Tauri (a strong red continuum with broad Hα), with the reflected Hα component showing a velocity of +37 km s^{-1} with respect to the star. By contrast, the new H-H object on the starward rim of Hind's nebula exhibited no continuum, but it possessed strong and relatively narrow emission lines of [S II], [O I], and Hα, with a velocity of -60 km s^{-1} with respect to the star. The similarity of the spectra of H-H objects to the spectra of quasi-stationary knots in supernova remnants led to the suggestion that the H-H nebulae are shock-excited by the interaction of a supersonic stellar wind with ambient material. The velocity field of the material around T Tauri supported the idea of a supersonic mass outflow, shocking against material which has a lower velocity away from the star.

The existence of polarization in HH 24, however, suggested the need for a compromise model. It was noted (Schwartz 1975) that H-H 24 tends to exhibit a higher level of red continuum than most H-H objects. It was suggested that the polarization was embedded in the continuum component which indeed is reflected from the IR source, but that the nebular emission lines should be unpolarized if produced in situ by shock waves at the site of the nebula. For example, if Hind's nebula and the adjacent H-H nebula near T Tauri were viewed from such an angle that the objects appeared superposed on one another, such a situation might arise. The original broadband polarimetric measurements of H-H 24 could not resolve this issue. However, Schmidt and Miller (1979) later made spectropolarimetric measurements of the knots in HH 24. It was found that the continuum indeed possessed high polarization (~ 25%), but that the nebular emission lines were unpolarized. Since the flux contribution of the emission lines and continuum were roughly comparable, the broadband polarization of ~ 15% could be understood as a dilution effect of the unpolarized nebular emission lines.

III. THEORETICAL MODELS

The recognition of the probable shock wave origin of H-H nebulae spawned a number of theoretical shock wave calculations and generalized models to account for the objects.

a) Numerical Shock Wave Calculations

Raymond (1976, 1979) and Dopita (1978b) were the first to use detailed steady-flow, plane-parallel shock wave calculations in attempts to model the spectra of H-H objects. It was found that shock velocities of 70-100 km s^{-1}, a pre-shock density of about 300 cm^{-3}, and solar abundances produced rough approximations to the optical spectra of H-H 1 and 2. The best fits were obtained with low fractional ionization of the pre-shock gas. The most significant departures from the fits involved the intensities of the neutral species [O I] and [N I] which are observed to be relatively stronger than predicted by the shock wave calculations.

In view of the clumpy morphology of H-H nebulae, one would not expect the observations to conform to the plane-parallel model predictions in detail. For example, a supersonic flow encountering a medium with density inhomogeneities will develop an irregular shock front with potential hot spots behind bow shocks associated with individual clumps. Large variations of post-shock temperature may exist from the head of a bow-shock to its more oblique outer regions. The lower temperature, oblique portions of such shocks may in fact yield enhancements of the low-excitation lines in comparison with the predictions of a plane-parallel shock. In addition, observations of very low-excitation H-H objects (to be discussed in section V) suggest that molecular hydrogen may play an important role in the shock waves. The shock wave calculations aimed at modeling H-H spectra have to date been limited to pre-shock gas in its atomic state.

b) Generalized Models

With the realization that the sources of excitation can be exterior to the H-H condensations, several scenarios emerged to account for the production of H-H nebulae. Schwartz (1978) suggested that a supersonic mass outflow from a young star could shock against ambient, dense cloudlets, producing the structure of H-H nebulae. The envelope of outflowing material was envisioned as having an optically thick dust component, re-radiating the light of the embedded star as IR radiation. The encounter of the wind with a distant dense cloudlet would generate a bow-shock on the starward side of the cloudlet. The pressure behind the bow shock would cause a shock wave to propagate into the cloudlet with a velocity $V_c = V_w/[1 + (n_c/n_w)^{1/2}]$ where V_w is the wind velocity with respect to the cloudlet, and n_c and n_w are the cloudlet and wind densities, respectively. The head of the bow shock would be identified with the bright condensation of an H-H object characterized by a shock velocity V_w. For conditions suitable to H-H 1 ($V_w \sim 100$ km s^{-1}, $n_w \sim 300$ cm^{-3}), a cloudlet shock with $V_c = 15$ km s^{-1} would develop if $n_c \sim 10^4$ cm^{-3}. If the cloudlet were composed of H_2, this could give rise to the H_2 IR emission observed by Elias (1980). Also, cloudlets accelerated by the wind would preferentially exhibit negative radial velocities (as observed) if only those ejected toward the front sides of dark clouds are visible. Furthermore, the bow shock velocity (V_w) would decrease as the cloudlet accelerated, leading to a high velocity object with low-excitation. The anti-correlation of velocities with excitation state of H-H objects was noted by Schwartz and Dopita (1980). Finally, it was argued that observed spectroscopic features such as the excess widths of the [O III] lines over the lower excitation lines and the strength of the neutral emission lines could be explained, at least qualitatively, by a bow shock. This model, however, faces several problems. First, if isotropic stellar winds are involved, mass loss rates of order 10^{-5} $M_\odot$ yr^{-1} are required, a figure which is 2 or 3 orders of magnitude higher than found in T Tauri stars. Second, it is not clear if momentum can be efficiently transferred from the wind to a cloudlet to produce the high velocities sometimes observed. Hydrodynamic calculations by Sandford and Whitaker (1982) suggest that the shock wave structure of a wind-cloud interaction is complex and may be dominated by a lee shock behind the cloud.

Norman and Silk (1979) proposed an "interstellar bullet" model in which a pre-T Tauri star develops strong radiation pressure or an intense wind which interacts with infalling natal material. The interface of the two flows develops a Rayleigh-Taylor instability which results in infalling clumps which are maintained at high density by the ram pressure of the wind which eventually sweeps the clumps outward. In the dense phase the clumps may be heated by turbulence from a Kelvin-Helmholtz instability, giving rise to H_2O maser emission. The clumps eventually emerge beyond the wind-cloud interface, plowing supersonically into the ambient medium to produce an H-H nebula in the shocked medium. The interaction would have some similarities to the Schwartz model, except that the bow shock would form on the side of the clump opposite the star, and the ambient medium would be shocked instead of the stellar wind. The arrangement of H-H 7-11 and the associated IR source in the NGC 1333 complex is suggestive of the Norman-Silk model since an H_2O maser source appears to be coincident with the IR source. One difficulty with the Norman-Silk model is that high cloudlet velocities should be correlated with high-excitation nebulae. In fact, HH 11 exhibits a very low-excitation spectrum with a high radial velocity (-150 km s^{-1}). Also, the identification of the exciting stars with a pre-T Tauri stage of evolution is questionable in view of the fact that at least five visible, relatively normal T Tauri stars (T Tau, HL Tau, AS 353A, RU Lup, and the C-S star) are known to be associated with H-H objects. It seems unlikely that these stars have only recently emerged from protostellar cocoons on a timescale (100-1000 years) consistent with the dynamical lifetime of H-H objects.

A third scenario was advanced by Cantó and Rodríguez (1980) who investigated the interaction of an isotropic stellar wind with a surrounding cloud which possesses a density gradient. The case suggested is that of a T Tauri star embedded in the outer part of a molecular cloud with decreasing density outward. In a steady-state flow, the wind evacuates an ovoid-shaped cavity distended toward the cloud boundary, with the stellar wind strongly refracted at the interface with the cavity. A shock wave identified with an H-H nebula is produced as the refracted, annular stream coverges to the distant outer tip of the ovoid near the cloud boundary. This model has the advantage of focusing the flow in such a way that more reasonable mass loss rates (10^{-7} - 10^{-8} $M_{\odot}$ yr^{-1}) can produce an H-H object. However, the model may not be able to produce high velocity H-H objects (Herbig and Jones 1981).

In view of the evidence for bipolar ejection of H-H objects to be discussed in section IV, recent work on stellar winds expanding into circumstellar disks is most appropriate. Barral and Cantó (1981) considered the effects of a large "interstellar disk" around a star,

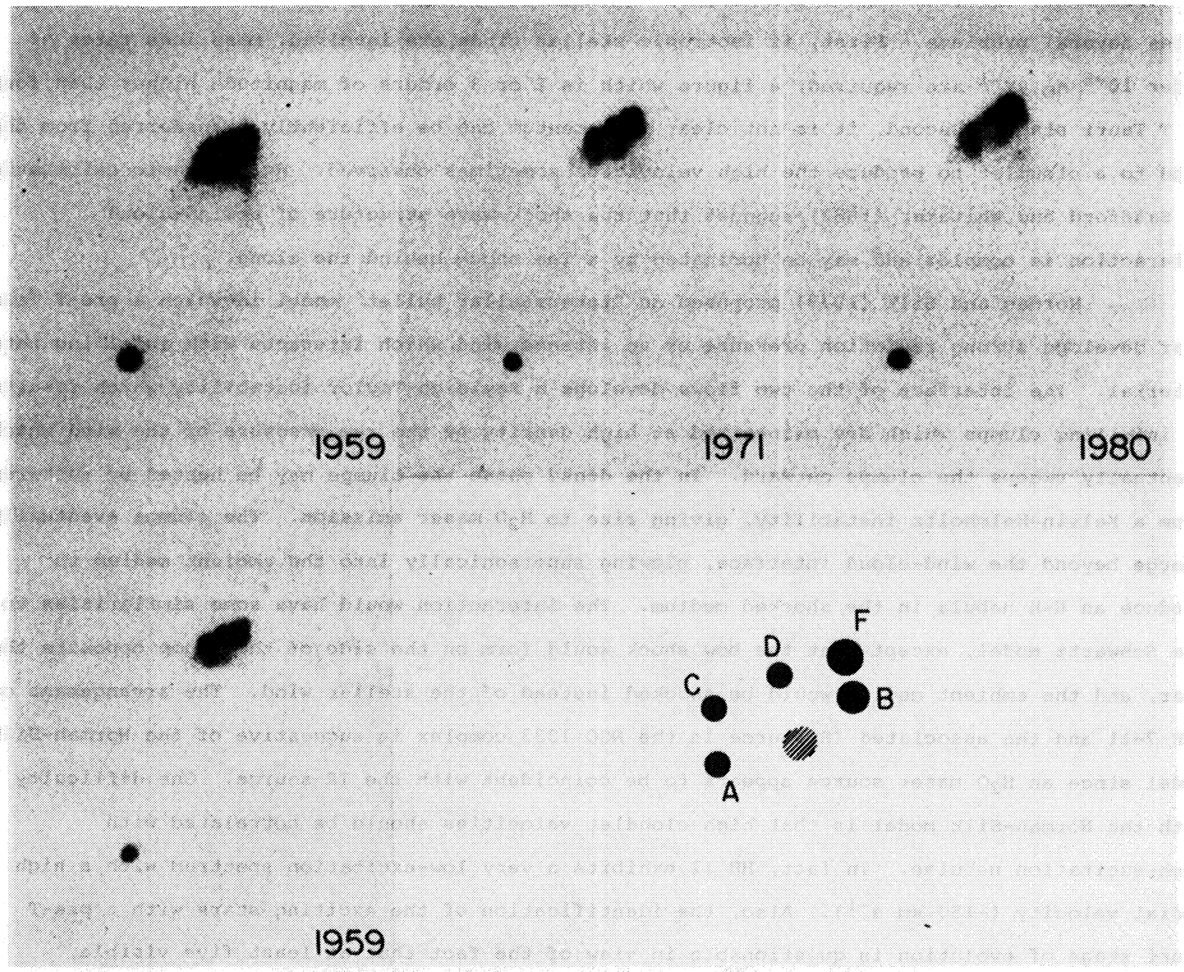

Fig. 1. Lick 120-in. plates of H-H 1 showing changes in structure. Short and long exposures are shown for 1959, and a sketch of the detailed structure of the knots is shown. The Cohen-Schwartz star is located at lower left, about 25" from H-H 1. (From Herbig and Jones 1981).

showing that an isotropic wind from the star will be focused into a bipolar flow. Cantó et al. (1981) interpret the morphology of Hubble's nebula (NGC 2261) and the nearby objects H-H 39 in terms of such a flow from R Mon. Königl (1982) has analyzed the problem in some detail with disk density distributions expected in protostellar environments. It is found that the expanding stellar wind bubble may become unstable to the formation of de Laval nozzels which channel the flow into oppositely-directed, supersonic jets. Material swept up by the jets or instabilities in the collimated flows could then be implicated with the H-H nebulae. In at least some cases, however, it is unlikely that a long-term steady wind is responsible for the jets. In several cases the stars identified as the exciting stars for H-H objects are rather quiescent objects, suggesting that the H-H objects must have been produced in earlier, eruptive events.

IV. SOME OBSERVATIONAL BENCHMARKS

Within the past ten years a great deal of observational material on H-H objects has been published. Remarkable new insights have arisen from work spanning a wide range of wavelengths from the ultraviolet to the radio portion of the spectrum. Here I will summarize a few of the more important discoveries.

a) Proper Motions and Radial Velocities

The existence of relatively large radial velocities in some H-H nebulae led to the expectation that some objects might exhibit large proper motions. In fact, Luyten (1963. 1971) reported the detection of substantial motion in H-H 28 and 29. These motions were confirmed by Cudworth and Herbig (1979) who found that the proper motion vectors were directed away from an IR source discovered by Strom et al. (1976) to be embedded in the L 1551 dark cloud in Taurus. Additional measurements of Lick plates revealed large proper motions of the knots in H-H 1 and 2 (Herbig and Jones 1980). Figures 1 and 2 are reproductions of Lick 3-m plates which exhibit the detail in these objects and variations which have occurred in the interval 1959-1980. The objects are moving in opposite directions from a faint T Tauri star (the C-S star) discovered by Cohen and Schwartz (1979) in an IR survey. The star is visible in the lower left frame of H-H 1 in Fig. 1. The proper motion vectors for the individual knots in H-H 1 and 2 are detailed in Fig. 3 where the lengths of the arrows represent projected 100 year motions which correspond to cross velocities of up to 300 km s^{-1} at the distance of the Orion complex. A third case is that of the proper motions in H-H 39 directed away from R Mon along the axis of Hubble's nebula (Jones and Herbig 1982). In the cases of H-H 28/29 and H-H 39, the objects appear to be associated with bipolar gas flows as revealed by radio CO observations to be discussed below.

The remarkable system H-H 46/47 exhibits radial velocities suggestive of bipolar ejection from a young star embedded in a cometary globule in the Gum Nebula (Dopita et al. 1982; Graham and Elias 1983). Figure 4, Bok's (1978) "Valentine's Night" photograph of this globule, shows the structure of this system. Whereas H-H 46 and 47A exhibit velocities of about -156 and -120 km s^{-1}, respectively, H-H 47C has a velocity of +102 km s^{-1}, indicating that it has only recently emerged in projection from behind the globule. Graham and Elias (1983) have studied this system in detail, finding evidence for the exciting star located near H-H 46. The alignment of this system is further evidence of strongly collimated flows from young stars.

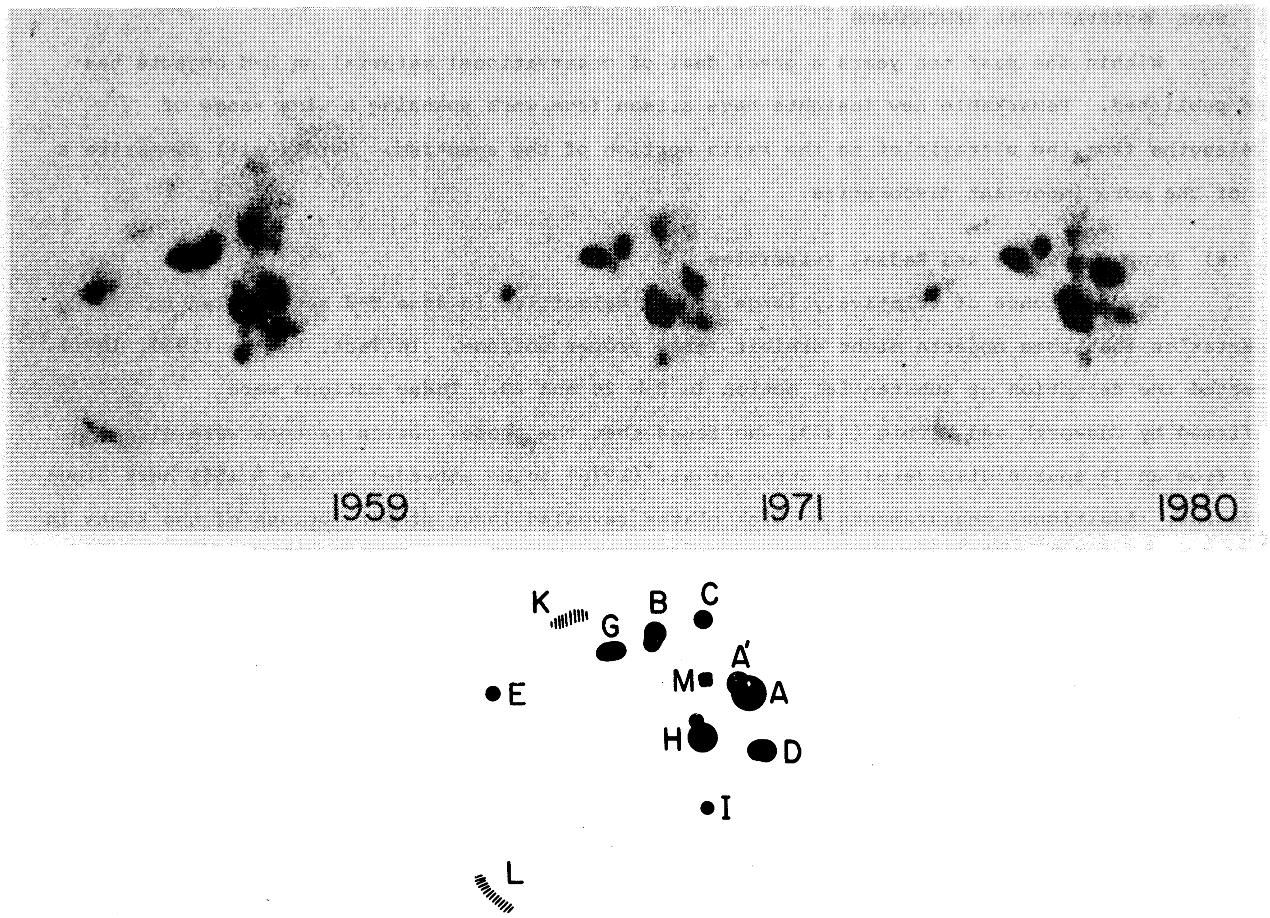

Fig. 2. Lick 120-in. plates of H-H 2 showing changes in structure. The 1959 exposure appears brighter than the other exposures because it was made with higher sensitivity emulsion. The complex knot structure is identified in the sketch. Each frame has an area of about 44" × 57". (From Herbig and Jones 1981.)

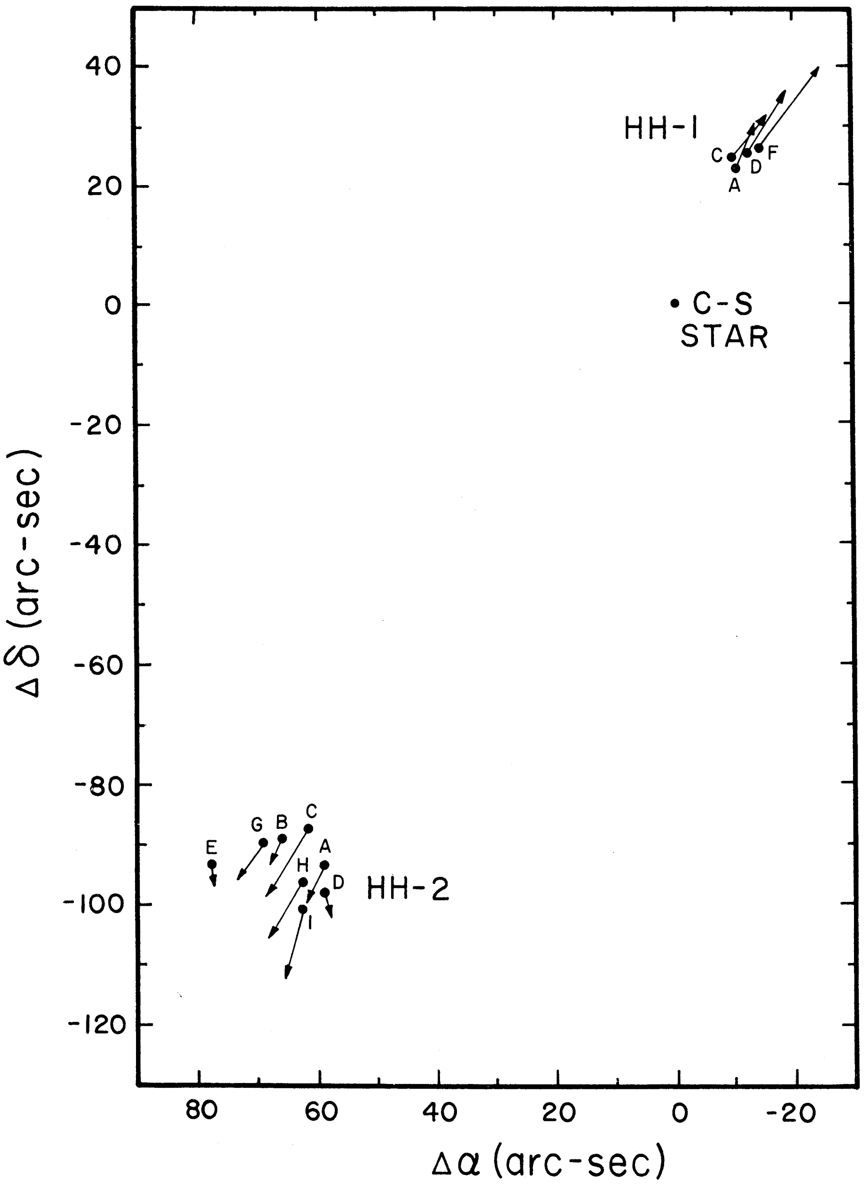

Fig. 3. The projected 100-year shifts due to the proper motions of the knots in H-H 1 and 2. The motions suggest an origin from the C-S star (Cohen and Schwartz 1979). (From Herbig and Jones 1981.)

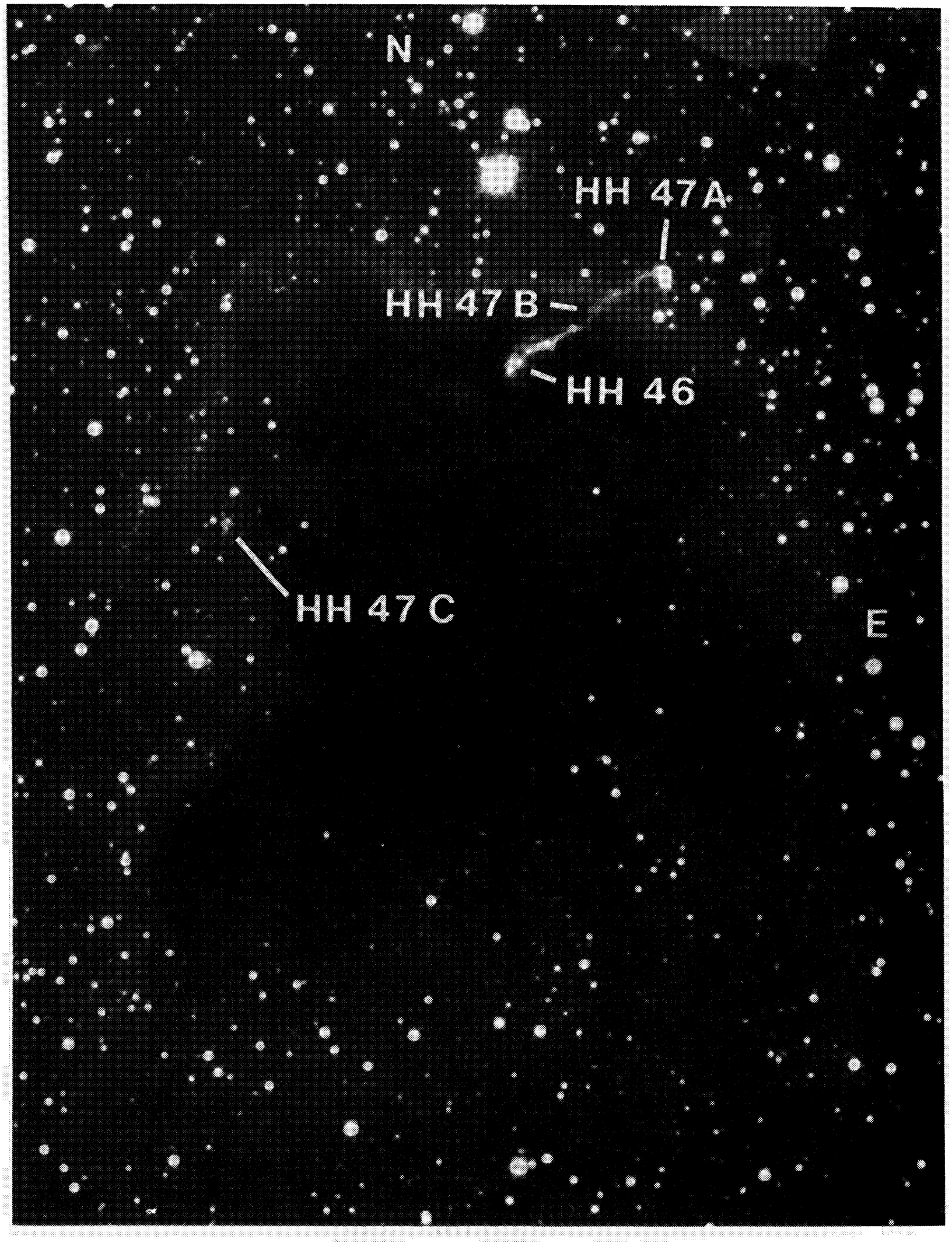

Fig. 4. Bok's (1978) photograph of the cometary globule EOS 210-6A which contains the H-H 46/47 system. Note that north is up and east to the right. An IR source is located near H-H 46 (Graham and Elias 1983). Whereas, H-H 46, 47B, and 47A exhibit large negative radial velocities, H-H 47C shows a large positive velocity. The alignment of the objects is suggestive of bipolar ejection from the IR star. (Photograph provided by B. Bok.)

b) Infrared Work

The important observations of the Stroms and their colleagues have been described briefly in section II. Surveys at 2 μm were initiated by Cohen and Schwartz (1979, 1980) in search of the exciting stars of the H-H nebulae contained in Herbig's (1974) catalog. With the strategy of searching 2' square areas centered on H-H nebulae to a limit of K $\lesssim$ 11.4, only a few probable exciting sources were discovered including the C-S star at H-H 1/2, and the H-H 7-11 exciting source which was a re-discovery of a source found previously by Strom et al. (1976). With the realization that sources are often aligned with H-H nebulae when two or more nebulae appear together, and with preliminary proper motion work on some of the H-H nebulae, the 2 μm search strategy became somewhat more efficient, allowing Cohen and Schwartz (1983) to detect probable exciting sources in 10 of 14 H-H nebulae investigated. Some of these sources have also been detected in the far-IR with the K.A.O. (Harvey et al. 1981, Cohen et al. 1983). Many of these sources have relatively small bolometric luminosities ($\lesssim$ 30 $L_\odot$) as judged from their energy distributions. However, a few sources are rather faint ($\lesssim$ 5 $L_\odot$), and at least one source (R Mon) is rather bright (~ 500 $L_\odot$), suggesting that the H-H phenomenon is not limited to sources in a specific luminosity range.

Elias (1980) has carried out IR spectrometry of a number of H-H nebulae, detecting the transitions of H_2 near 2 μm. The brightest H_2 source appears to be the southern object H-H 54 (Schwartz 1977b). Beckwith et al. (1978) had earlier detected the H_2 transitions in the vicinity of T Tauri. The excitation is best explained by shock wave heating in low velocity shocks (10-20 km s^{-1}).

c) Radio Observations

A number of radio studies have probed the physical conditions in the molecular clouds which harbor H-H objects. For a detailed account of this work the reader is referred to the reviews of Cantó (1981) and Schwartz (1983b). Here I would like to highlight the important observations in which anisotropic mass flows were found to be associated with H-H IR sources. Although Knapp et al. (1976) first detected a low-velocity wing in the ^{12}CO emission line in the vicinity of H-H 102 in the Taurus L 1551 dark cloud, it was the CO measurements of Snell et al. (1980) that revealed broad velocity features with redshifted CO in a lobe to the NE of L 1551 IRS 5, and blueshifted CO in a lobe to the SW of the IR source. The high proper motion objects H-H 28 and 29 are located in the blueshifted lobe. It was suggested that the H-H objects represent material caught and shocked in a bipolar flow from the IR source. A similar CO bipolar flow was discovered by Snell and Edwards (1981) to be associated with the IR source at the head of the H-H 7-11 chain. Figure 5 demonstrates that the H-H objects are again located in the blueshifted CO lobe. Any H-H objects associated with the redshifted lobe would presumably be optically obscured since that lobe is plowing deeper into the molecular cloud. Evidence for bipolar flows from the IR sources associated with H-H 24 and H-H 25/26 (Snell and Edwards 1982) and with H-H 39 (R Mon) (Cantó et al. 1981) has also been reported. Edwards and Snell (1982) found high velocity CO flows associated with T Tau, AS 353A, and HL Tau out of 28 T Tauri stars

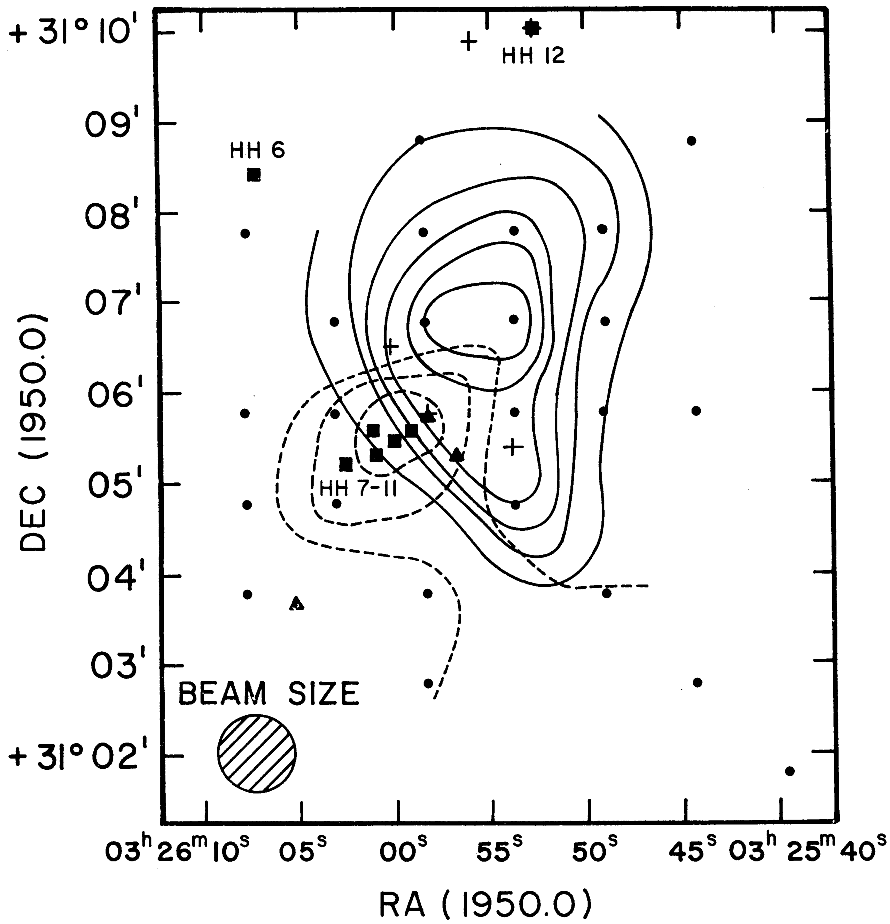

Fig. 5. The bipolar CO flow associated with the H-H 7-11 IR source. The embedded star (+) is located about 15" NW of the chain of H-H objects, and it is coincident with an H_2O maser source (triangle). The dashed contours represent the blueshifted CO lobe, and the solid lines represent the redshifted lobe. (From Snell and Edwards 1981.)

mapped. It is probably significant that each of the three stars detected possess nearby H-H objects.

d) Optical Studies

Herbig (1974) has compiled a catalog of 42 H-H objects located mainly in the NGC 1333 complex, the Taurus-Auriga dark clouds, and the Orion complex. Schwartz (1977a,b) reported 14 additional objects from an objective prism survey of southern T-associations in Chamaeleon, Lupus, and Norma. A number of other observers have reported discoveries of H-H nebula, and the reader is referred to the review by Schwartz (1983b) for a more complete account of H-H identifications.

The first well-calibrated spectrophotometric measurements were made on H-H 1 and 2 by Böhm et al. (1974, 1976). In the study of Böhm et al. (1974) a faint blue continuum was seen with flux increasing toward shorter wavelengths. A subsequent study by Brugel et al. (1981a) confirmed the behavior of the continuum, finding $F_\lambda \propto \lambda^{-n}$ with $2.0 \lesssim n \lesssim 2.9$ for six objects. The source of this blue continuum has only recently been identified and it will be discussed in section V.

Brugel et al. (1981a,b) reported emission line intensities for 12 northern H-H nebulae, and Dopita (1978) measured 18 objects (including southern H-H's), modeling the emission line strengths with the use of his shock wave code. Schwartz and Dopita (1980) combined spectrophotometric and radial velocity data on six southern H-H objects with similar data on 20 northern objects, and discovered an anti-correlation between velocities and excitation states. The lowest excitation objects tend to show the highest velocities, suggesting that the flows responsible for the shocks are encountering material which already possesses a substantial velocity away from the star. The difference in the velocities between the flow and the ambient material determines the excitation state of an object. Schwartz (1978, 1981) has obtained high dispersion photographic spectra of several H-H objects, finding that the nebular emission lines have widths generally less that 2 Å, with the higher excitation lines (e.g., [O III]) exhibiting the greater widths.

Broadband optical polarization measurements on H-H nebulae have been carried out by Strom, Strom, and Kinman (1974), Schmidt and Vrba (1975), King and Scarrott (1981), and Vrba et al. (1975). In addition to H-H 24 discussed in section II, H-H 100 in the Corona Austrina complex exhibits significant polarization (Vrba et al. 1975). Cohen and Schmidt (1981) have carried out spectropolarimetry on H-H 30, discovering unpolarized nebular emission lines but a polarized continuum which probably originates in reflection from the T Tauri star HL Tau.

e) Ultraviolet Work

Considering the faintness of H-H nebulae, their low-excitation character, and their locations in or near obscuring dark clouds, it was somewhat surprising when Ortolani and D'Odorico (1980) reported detection with the I.U.E. of both UV continuum and emission lines (C II, C III], N III], and C IV) in H-H 1. The continuum, although only weakly exposed, appeared to increase with decreasing wavelength in the range $1200 \lesssim \lambda \lesssim 2000$ Å. Böhm et al. (1981) extended the I.U.E. observations of H-H 1 to the range $2000 \lesssim \lambda \lesssim 3000$ Å, and combined with new observations of the short wavelength range, 15 emission lines were identified. The noisy continuum, averaged over 100 Å bins, exhibited a steep flux increase ($F_\lambda \propto \lambda^{-6.9}$) in the range from 3000 Å to 2400 Å, with a more gentle increase to 1200 Å. Böhm-Vitense et al. (1982) have recently reported that the UV spectrum of H-H 2H is similar to that of H-H 1. Also, extended UV emission appears to be associated with the C-S star near H-H 1 (Böhm and Böhm-Vitense 1982).

Initial speculation on the origin of the UV continuum assumed that it was scattered radiation from an embedded star. However, Böhm et al. (1981) concluded that even an extreme T Tauri star could not produce such a reflection spectrum assuming reasonable dust scattering properties. It was concluded that a very hot star close to the H-H object would be required if the continuum had a stellar origin. The absence of any such star as indicated by optical and IR observations thus heightened the continuum mystery. A second enigma concerns the co-existence of relatively high-excitation UV emission lines (esp. C III], N III], and C IV) with strengths which are inconsistent with the temperatures required to produce the optical spectra in H-H 1 and 2H. We will address these mysteries and discuss some recent work which suggests a resolution of the problems in the following section.

V. SOME RECENT OPTICAL/ULTRAVIOLET STUDIES

a) The Two-Photon Continuum

Dopita (1981) first suggested that the blue-UV continuum excess in H-H nebulae might derive from an enhanced two-photon (2q) emission from collisionally-excited hydrogen. Evidence favoring this hypothesis was obtained by Dopita et al. (1982) in a spectrophotometric study of 10 H-H nebula. A sample of one of the spectra (H-H 2H) obtained with the Anglo-Australian Telescope is reproduced in Figure 6. The flux scale has been selected to demonstrate the level of the continuum. Continuum intervals were chosen as indicated to avoid obvious emission lines, and fluxes corrected for reddening were averaged over the intervals.

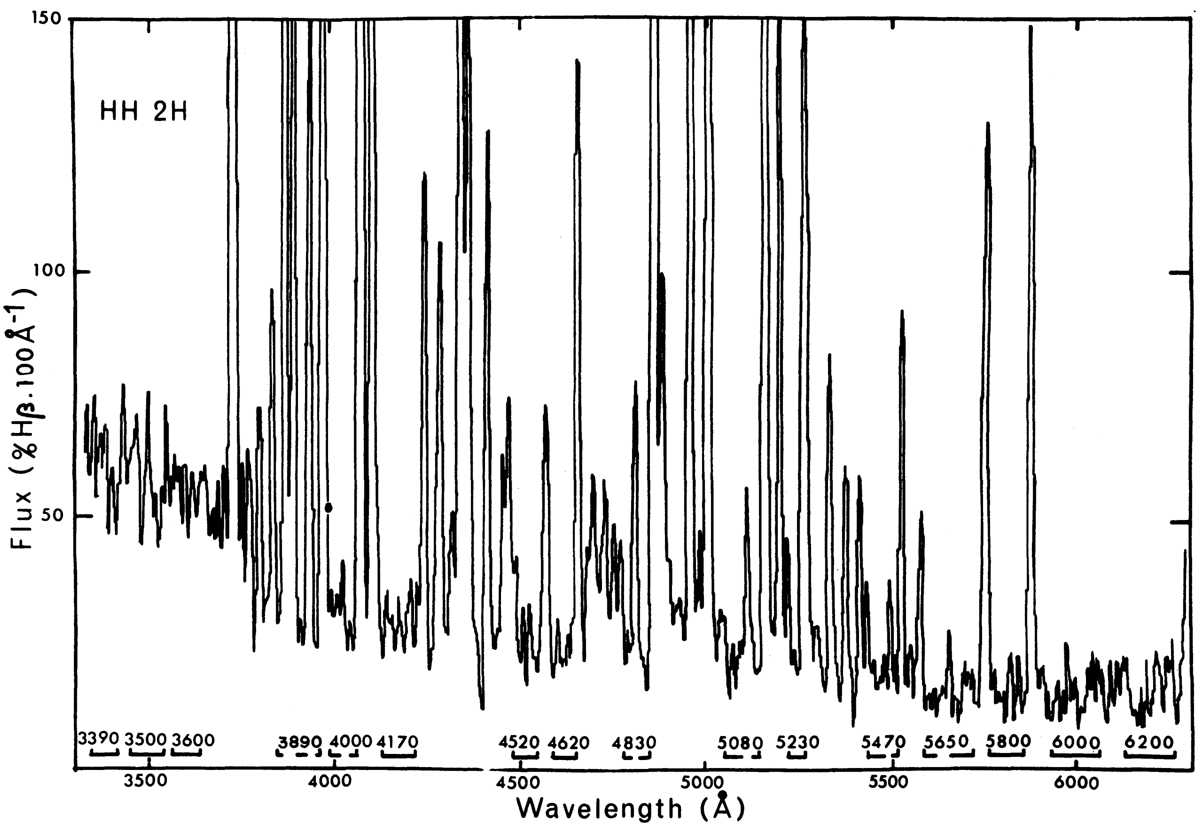

Fig. 6. The spectrum of H-H 2H obtained with the A.A.T. The spectrum is scaled to exhibit the continuum level (on this scale Hβ has an intensity of about 1500). Intervals chosen for continuum measurements are indicated. The emission lines (H, [S II], Mg I], Ca II, [Fe II], [O II], [O III], [N I], etc.) have been identified in previous studies (see Böhm et al. 1973). (From Dopita et al. 1982).

A simple one-parameter curve-fitting procedure was attempted for the continuum flux distributions in each of the 10 H-H objects. It was assumed that the continuum consisted of a combination of free-bound emission ($F_{fb} \propto \lambda^{1.1}$) and 2q emission ($F_{2q} \propto \lambda^{-3.3}$ in the range investigated), with the Balmer jump and free-bound contributions appropriate for a 10^4 K gas. The free parameter, f_{2q}, is a multiplicative factor by which the 2q continuum is enhanced in order to achieve a best fit to the observed data when added to the free-bound component. The factor f_{2q} is normalized for the case of a pure recombination spectrum, in which case it has roughly 20% of the intensity of the λ 3645- Balmer free-bound continuum. The curve-fitting procedure is expressed in schematic form in Figure 7. Remarkably good fits were achieved for each of the H-H objects, but rather large 2q enhancement factors (f_{2q}) ranging from 2.8 for H-H 2A to 13.3 for H-H 47 were required. The results of the exercise are displayed in Figure 8 where the H-H objects are arranged in order of increasing f_{2q} from bottom to top.

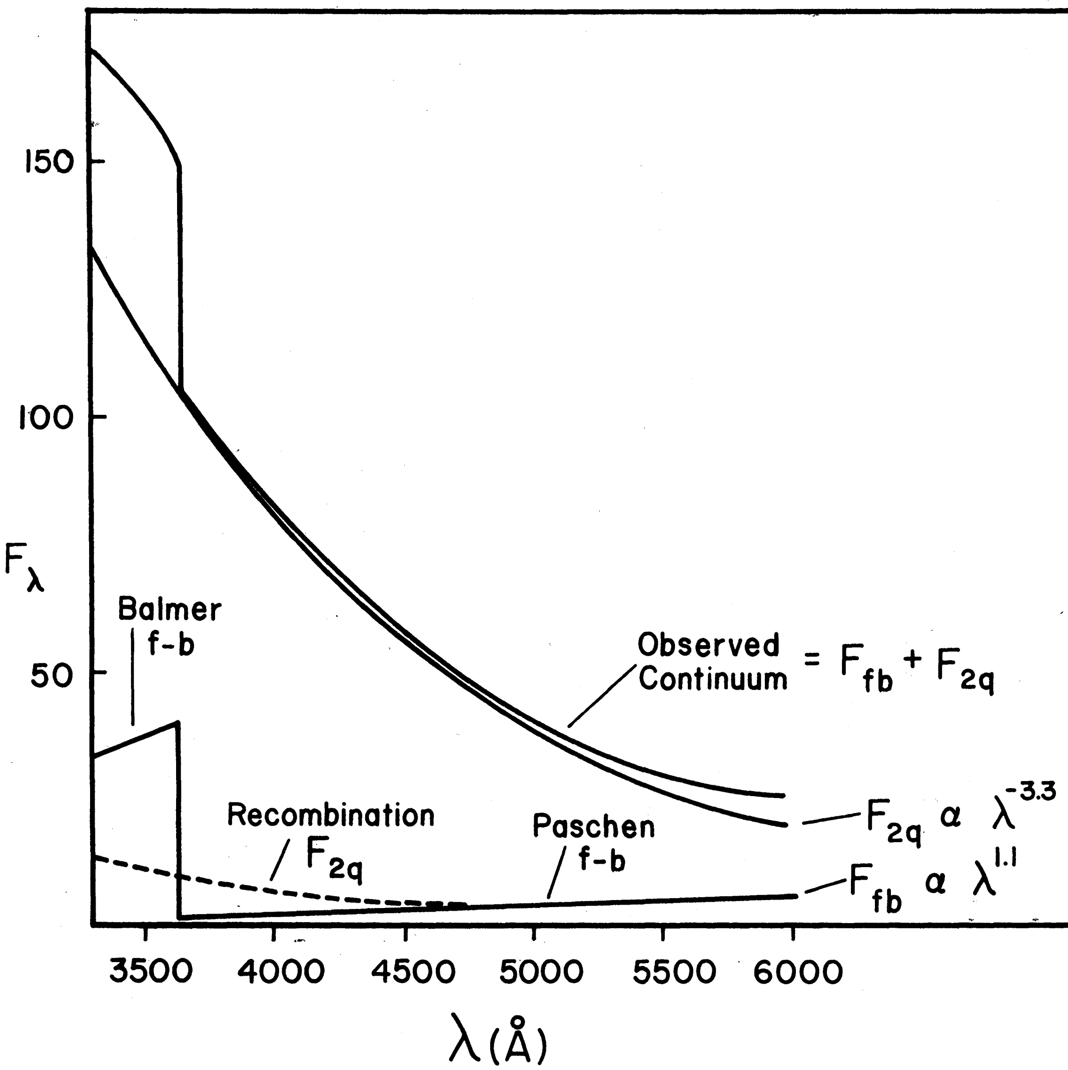

Fig. 7. A schematic of the fitting procedure for the blue-UV continuum in H-H nebulae. The recombination 2q spectrum is that expected from a pure cascade spectrum. The recombination 2q spectrum is multiplied by an enhancement factor (f_{2q}), and the result is added to the free-bound Balmer and Paschen continua to achieve a fit to the observed continuum.

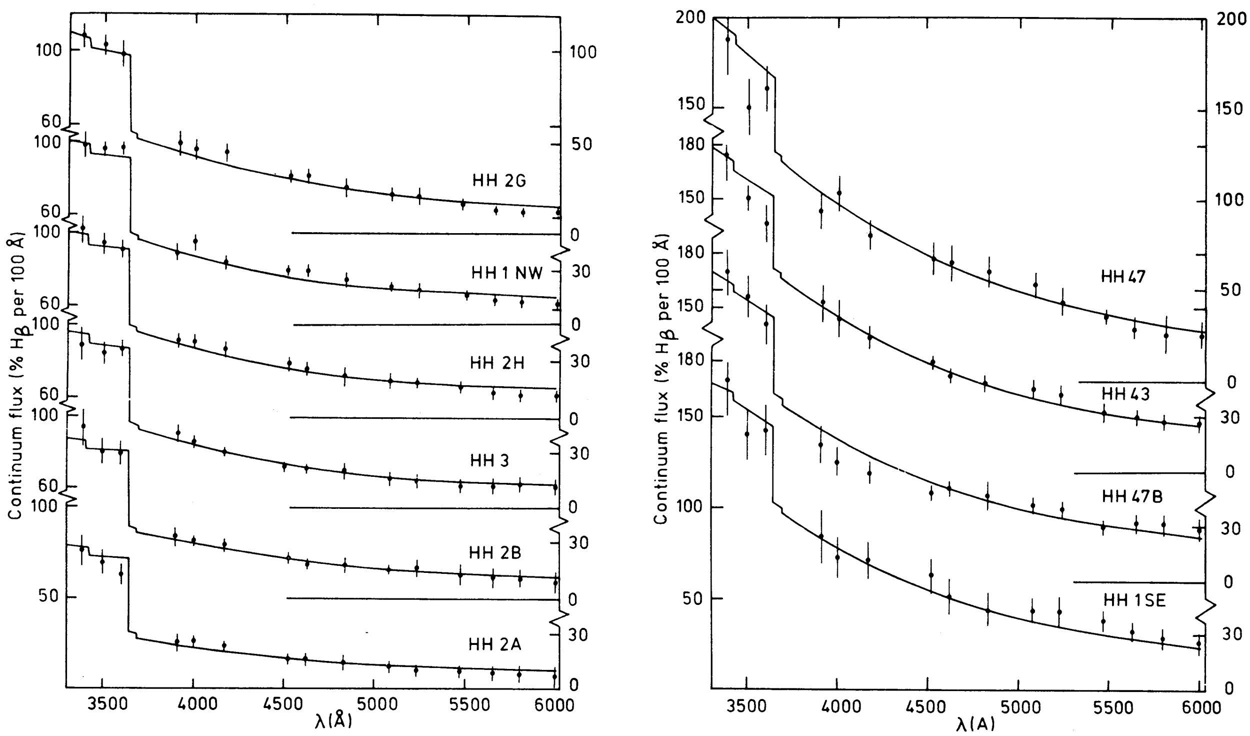

Fig. 8. A montage of curve fits to the continuum points of H-H objects. The curve-fitting procedure is sketched in Figure 7. Among the objects observed, H-H 2A requires the least 2q enhancement (f_{2q} = 2.8), and H-H 47 requires the greatest enhancement (f_{2q} = 13.3). (From Dopita et al. 1982.)

A clue to understanding the 2q enhancement can be seen in Figure 9 which is a plot of an excitation parameter [log (6300/5007)] vs. log f_{2q}. A correlation is evident in that those objects with the lowest excitation (i.e., [O I] >> [O III]) tend to exhibit the highest relative continuum levels (i.e., the largest f_{2q} factors). A similar correlation is present between the Balmer decrement and f_{2q}. The relationships suggest that the excitation of H-H nebulae is dominated by collisional processes as one would expect in shocks of relatively low velocity. Dopita et al. (1982) carried out detailed shock wave computations in an attempt to reproduce both the 2q enhancement and the relative intensities of emission lines in the lowest excitation objects, H-H 43 and 47. Although 2q enhancement factors of up to $f_{2q} \approx 5$ could be achieved in a steady-flow shock with a large neutral fraction (95%) of pre-shock gas and a shock velocity of about 40 km s^{-1}, the large enhancement factors for H-H 43 and 47 (f_{2q} = 11 and 13, respectively) could be produced only by assuming a time-truncated shock. By sawing off the latter portion of a steady-flow shock wave, one effectively creates a finite-age shock in which the recombination zone has not yet fully developed. Collisional excitation of hydrogen dominates, and at relatively low temperatures and densities the 2s level of hydrogen remains highly populated,

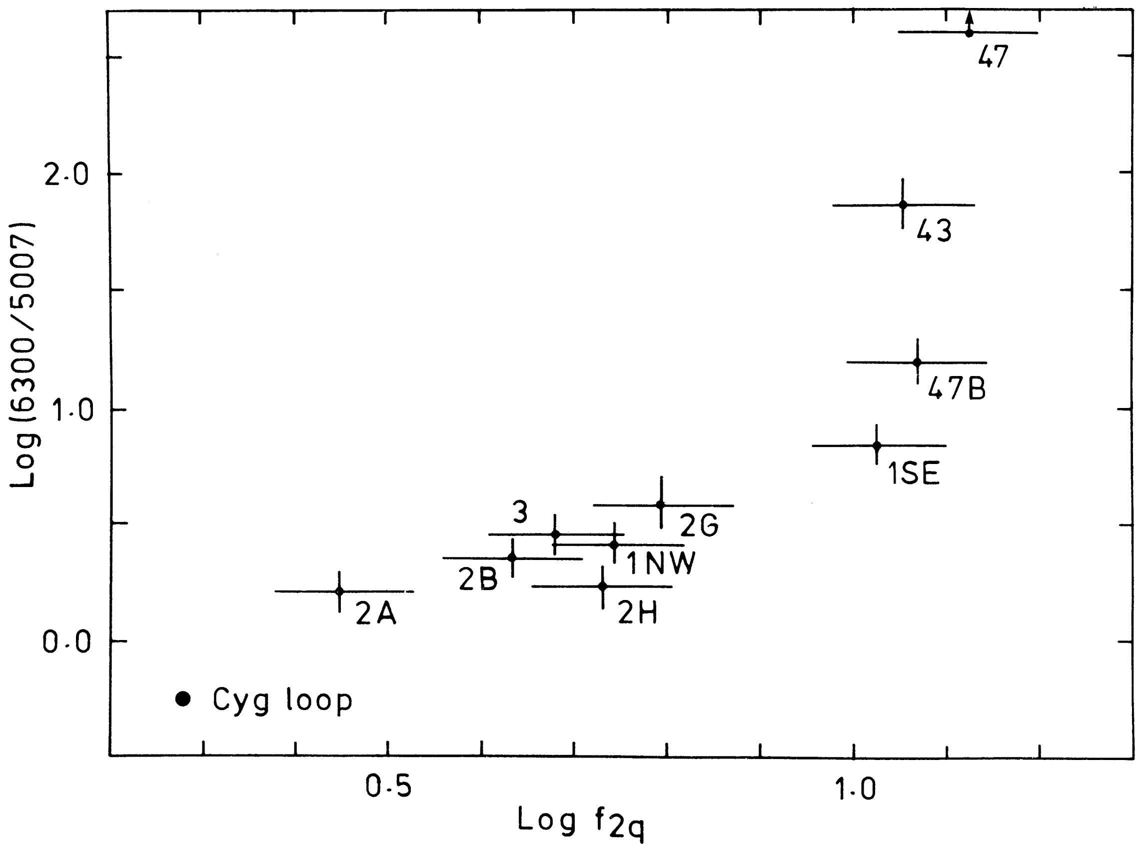

Fig. 9. The correlation of the 2q enhancement factor with the excitation state of H-H nebulae. The ordinate represents decreasing excitation with increasing values of the ratio [O I] 6300/ [O III] 5007. (From Dopita et al. 1982).

leading to the 2s → 1s 2q transitions which are considerably enhanced over what prevails in a pure recombination cascade. Also, the relative emission line intensities in these objects could be approximately matched with the time-truncated models.

The most compelling evidence for 2q emission would lie in the detection of the 2q flux peak in the range λλ 1400-1500 Å, with the flux falling rapidly to zero at 1216 Å. The early I.U.E. measurements of H-H 1 and 2H were hindered by low signal to noise, and at the low spectral resolution of the measurements there was some uncertainty as to the possible contribution of unresolved, weak emission lines to a "pseudo-continuum." Recently, Brugel et al. (1982) have obtained additional I.U.E. spectra of H-H 2H, and the improved signal suggests for the first time the presence of a peak in the continuum near 1450 Å which is taken as evidence for the 2q continuum. In that study, the results of shock wave calculations to reproduce the 2q continuum were also reported. In view of the UV observations to be discussed below, one should look with caution at shock wave models which assume only atomic pre-shock gas. There is evidence for a sizeable component of H_2 in the lower excitation H-H objects, and this would obviously modify the results of shock wave calculations.

b) The UV Spectra of Low-Excitation H-H Objects

Motivated by the study of Dopita et al. (1982) which predicted the greatest relative 2q enhancements for the lowest excitation objects, I recently obtained I.U.E. spectra of H-H 43 and 47 (Schwartz 1983a). The short wavelength spectra of these two objects, corrected for

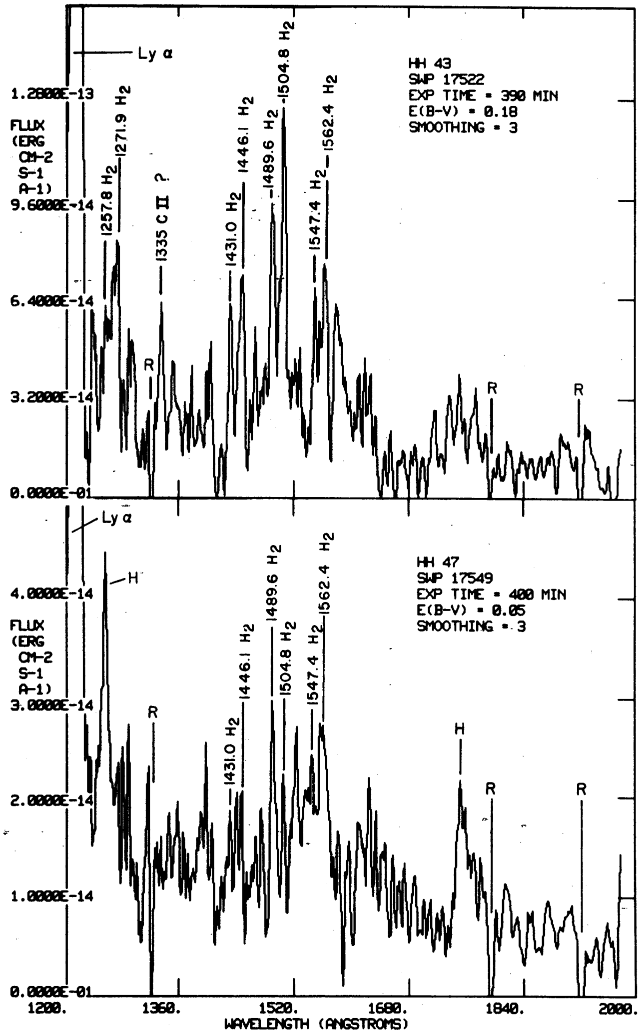

Fig. 10. The short wavelength I.U.E. spectra of H-H 43 and 47. The symbol H represents cosmic ray hit blemishes, and R designates reseau markes internal to the imaging system. The Lyman α line is due mainly to geocoronal emission. The H_2 emission lines shine by fluorescence after being excited by Lyman α as shown in Figure 11. (From Schwartz 1983a.)

reddening, are shown in Figure 10. The greatest surprise was the detection of a series of Lyman band H_2 emission lines in H-H 43 and probably in H-H 47. These lines were first discovered in the spectra of sunspots (Johnston et al. 1971), and are produced by fluorescence with Lyman α serving as the pump. Also, the lines were detected with the I.U.E. in Burnham's nebula at T Tauri by Brown et al. (1981), thus their appearance in H-H 43 and 47 becomes less surprising. The transitions occur between the electronic $^1\Sigma_g^+$ and $^1\Sigma_u^+$ states of the H_2 molecule as displayed in Figure 11. The pumping transition is about 0.38 Å to the red of the central wavelength of

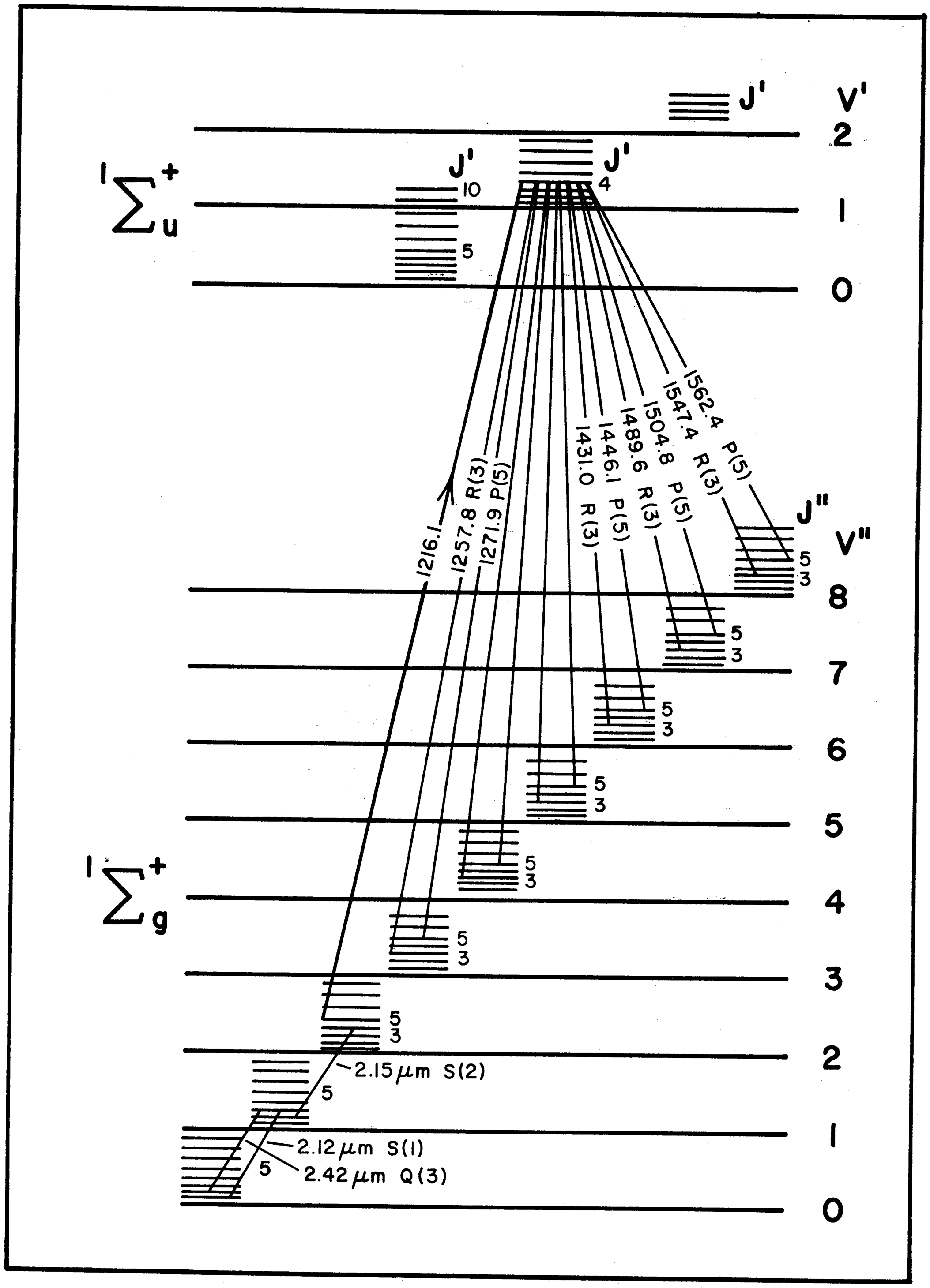

Fig. 11. A sketch of the energy states responsible for H_2 Lyman band fluorescence. The energy level separations are schematic only and do not represent a correct scaling. The pumping transition (1216.1 Å) is about 0.38 Å longward of the central wavelength of H Lyman α. The transitions to the v" = 5, 4 states have wavelengths of λ 1387.4 P(5), λ 1372.5 R(3); and λ 1329.1 P(5), λ 1314.6 R(3), respectively. However, the transition probabilities for these lines are low and the lines are not observed in H-H 43 or 47. Whereas the UV lines represent electronic-vibrational-rotational transitions, the near IR lines seen in some H-H objects are vibrational-rotational transitions. Transitions detected by Elias (1980) are indicated between the first three vibrational states of the ground electronic state. Excitation of H_2 to the v" = 1, 2 states evidently is caused by shock wave heating.

Lyman α. The relative intensities of the 8 lines seen in H-H 43 agree reasonably well with their transition probabilities. For the pump to operate, the v" = 2, J" = 5 levels of the ground electronic state must be excited, a feature which is easily accomplished by shock-heated gas at 2000-3000 K. In Figure 11, the infrared transitions within the electronic ground state which Elias (1980) has seen in H-H objects are also noted.

The continuum in each of the objects was studied by selecting 100 Å wide bins separated by 50 Å, and computing the average flux in each bin (which includes emission lines). A second approach was to choose continuum intervals which are free of obvious emission lines and compute mean fluxes. The results of this exercise are displayed in Figure 12. In both cases there is evidence that the continuum peaks in the vicinity of 1500 Å, confirming its probable 2q

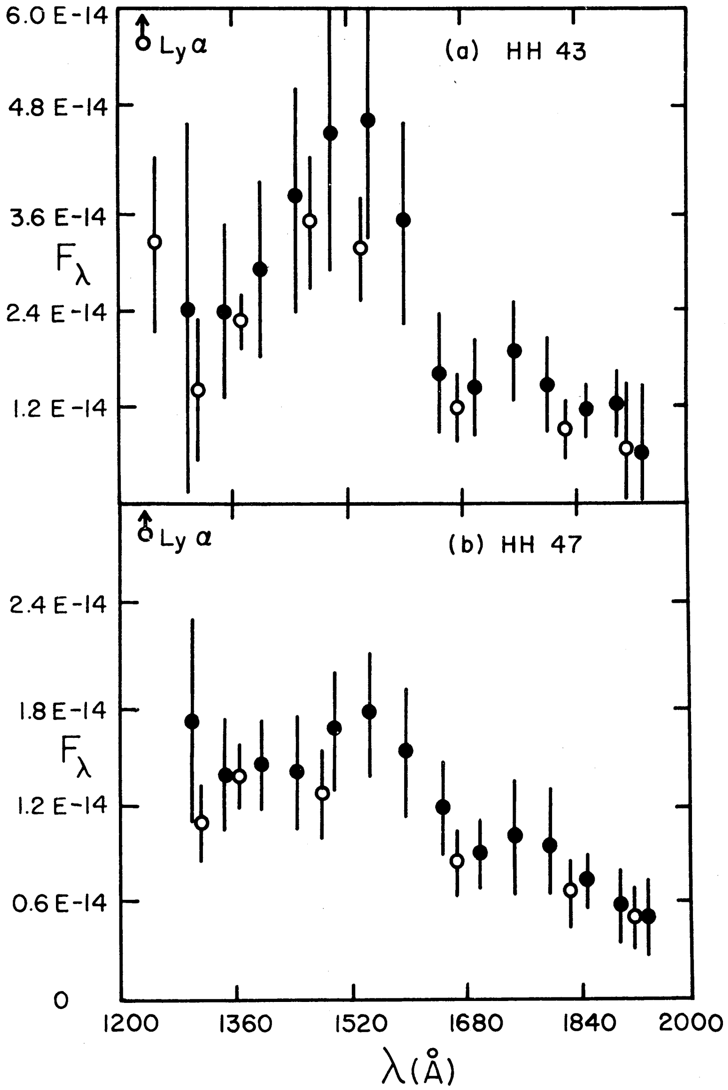

Fig. 12. The UV continuum distributions in H-H 43 and 47. Solid circles represent average fluxes in 100 Å bandwidths (emission lines included) with 50 Å separations. The open circles represent bands chosen to avoid obvious emission lines. The peak in the flux in the vicinity of 1500 Å is probably due to two-photon continuum. (From Schwartz 1983a.)

origin. However, it is apparent that additional emission is occurring in the interval $1200 \lesssim \lambda \lesssim 1500$ Å, and higher resolution, deeper UV spectra will be required to determine if this region contains a mat of emission lines.

c) The Optical-UV Emission Line Dilemma

The optical spectra of H-H 43 and 47 exhibit extremely low-excitation emission lines (see Dopita 1978a,b) with only neutral and once-ionized species observed (except for very faint [O III] emission in H-H 43). Thus one would expect none of the higher excitation UV intercombination lines and resonance lines (other than the Lyman lines of H, etc.) typical of high temperature nebulae, and indeed Figure 10 indicates that such lines are not present. However, we have noted that observations of H-H 1 and H-H 2H present quite a different picture with relatively strong UV lines of N III], C III], and C IV, but only moderate to weak lines of [O III] and [Ne III] in the optical range which is dominated by low-excitation lines.

Böhm et al. (1981) and Böhm-Vitense et al. (1982) have pointed out that a single velocity shock is not capable of producing a combined high-excitation UV spectrum and a lower excitation optical spectrum as observed in H-H 1 and 2H. Brugel et al. (1982) have suggested that shocks at two different velocities, if co-added, could yield both the low-excitation and high-excitation portions of the spectrum. At the University of Missouri, R. Heuermann and I have begun investigations of the "two-shock" model. Such a model is a very crude approximation, for example, to a bow shock which would have a high temperature region at the head of the bow shock and a more extended, lower temperature region behind the more oblique bow wave.

We have used the shock wave code MAPPINGS developed by Dopita et al. (1982) at Mt. Stromlo for preliminary calculations of two-shock models. A typical result is displayed in Table 1 where the intensities of selected lines from the "cool" and "hot" shocks are listed separately in columns 3 and 4. Note that the cool shock falls far short of matching the UV line intensities and the [O III] intensity for H-H 2H listed in column 6, whereas the hot shock produces a better match to the UV line emission, but overestimates the [O III] line by a significant factor. Taking into consideration that the 3×10^5 K shock emits about 2.34 times more Hβ per column volume than the 10^5 K shock, one can arbitrarily increase the effective area of the cool shock, co-add to the hot shock intensities, and finally renormalize to Hβ = 100. This is done in column 5 for a cool/hot shock ratio of 3. It could be argued that the hot shock model alone is a better fit to the observed intensities in column 6. However, the combined shock spectrum shows that the relative intensity of the [O III] line can be reduced by sacrificing UV line intensities. At first sight this might appear to pose a severe problem, but it is important to note that the interstellar extinction curve is very poorly known for the UV range, and it is very possible that the observed UV intensities have been over-corrected by a factor of two or more relative to Hβ. Given the very preliminary nature of this work, it is not possible to assert that the "two-shock" model is necessarily to be preferred to other remedies. It does suggest that more thorough-going shock wave calculations with non-planar geometry might be fruitful. Also, the effects of time-truncation on the two shocks should be investigated.

TABLE 1. Relative Emission Line Intensities for Cool and Hot Shocks Compared with H-H 2H

Line	λ	"cool" I_λ[1]	"hot" I_λ[1]	Combined Shocks 3:1	H-H 2H[2] Observed
C IV	1549	8×10^{-4}	407	179	521
O III]	1663	.1	113	50	255
N III]	1747	4×10^{-2}	14	6	59
C III]	1909	11	540	243	392
Mg II	2800	226	192	212	304
[O II]	3726/29	295	360	323	199
Hβ	4861	100	100	100	100
[O III]	5007	2	308	136	81
[O I]	6300	83	92	86	145
Hα	6563	313	293	305	377
[N II]	6583	85	131	105	201
[S II]	6717	74	51	64	48
[S II]	6731	134	113	125	95

	"cool"	"hot"
Pre-shock density	300 cm^{-3}	300 cm^{-3}
Pre-shock ionized fraction	0.4	0.9
Shock velocity	69.6 km s^{-1}	139.8 km s^{-1}
Post-shock temperature	10^5 K	3×10^5 K
Log F(Hβ)	-4.014	-3.644

1 Solar Abundances, zero magnetic field.

2 Corrected for reddening of E(B-V) = 0.34. The UV intensities are from Brugel et al. (1982); the optical intensities are from Dopita et al. (1982).

VI. CONCLUDING REMARKS

Within the past few years a combination of observational data over a wide spectral domain and theoretical shock wave calculations have led to a reasonably coherent picture of the nature of H-H nebulae. The ionization and excitation of the nebulae appear to be dominated by collisional processes in shock waves with shock velocities in the range 40 - 140 km s^{-1}, and pre-shock densities of 50 - 300 cm^{-3}. Although a few objects exhibit a red continuum which is polarized and thus is probably the product of reflection from an exciting star, probably all H-H nebulae exhibit a blue-UV continuum which is the product of collisionally enhanced nebular two-photon emission.

Observations of anisotropic CO flows, proper motions of H-H objects, and linear alignments of the nebulae with exciting IR sources in a number of cases suggest that the supersonic flows are highly collimated. In at least five cases H-H nebulae are associated with T Tauri stars, and in most other cases the IR energy distributions of embedded sources are consistent with those of T Tauri stars. However, the present state of many of these exciting stars appears to be rather quiescent, thus the H-H nebula may have been produced in eruptive events. Moreover, the bipolar nature of the supersonic flows suggest that outflowing matter may be focused by circumstellar disks.

Examination of the systems H-H 1-3 and H-H 46-47 reveals some tantalizing clues which must bear upon the ultimate origin of the H-H objects. First, these two systems clearly exhibit H-H objects moving in opposite directions from a central star. However, in each case the H-H objects are displaced by different amounts from the star, suggesting that the objects were ejected at different times. This is demonstrated by the sketches for these systems shown in Figure 13. For H-H 1 and 2, the tangential velocities are computed from the proper motions

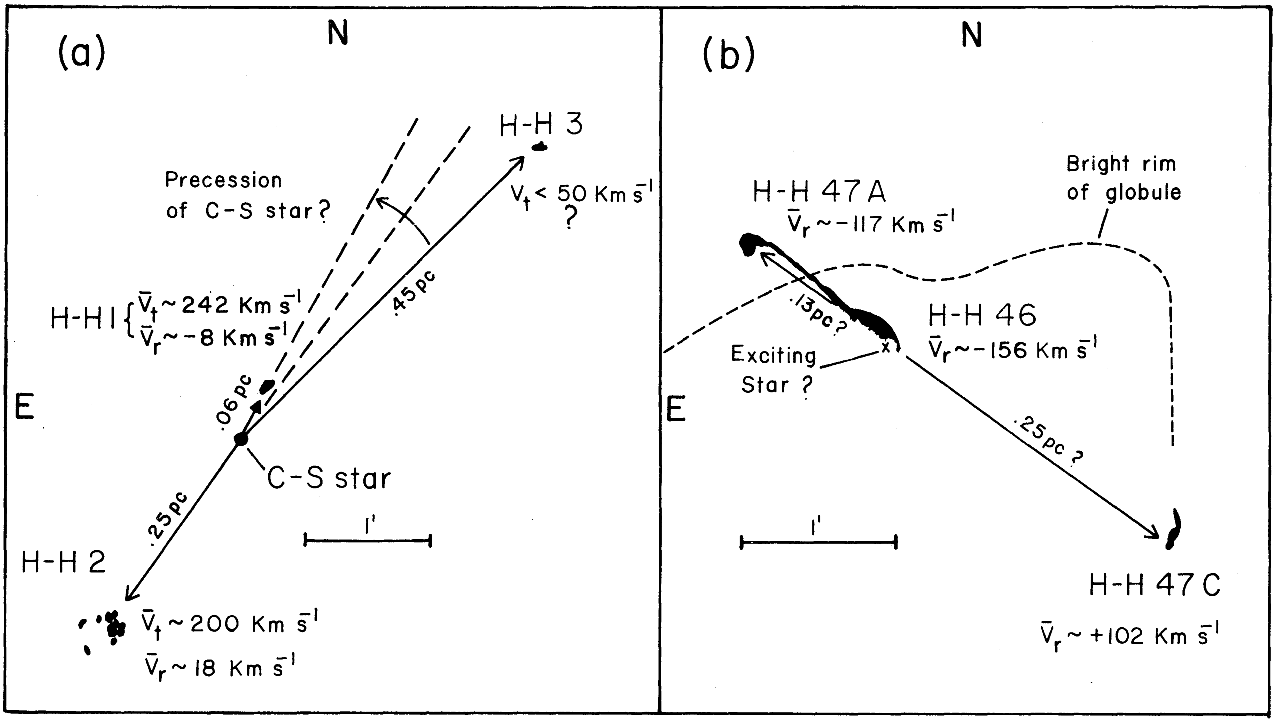

Fig. 13. The H-H 1-3 system (a) and the H-H 46-47 system (b), demonstrating the effect of quasi-periodic, alternate north and south polar ejections of H-H objects. A distance of 460 pc is assumed for H-H 1-3, and the globule associated with H-H 46-47 is assumed to be at a distance of 400 pc. Whereas the motions of H-H 1-3 are mostly in the plane of the sky, the radial velocities in H-H 46, 47A, and 47C suggest that the system has a significant inclination. The distance of H-H 47A and 47C from the exciting star are hence projected distances on the plane of the sky.

found by Herbig and Jones (1981) assuming a distance of 460 pc. The (heliocentric) radial velocities are averages from the work of Schwartz (1978). It is apparent that the axis of ejection lies almost entirely in the plane of the sky, with a possible slight inclination toward earth to the north and west of the C-S star. The limit on v_t for H-H 3 is a conservative estimate based upon the lack of proper motion as seen on the Crossley plates (Herbig and Jones 1981).

The sketch suggests that the objects have been ejected in a quasi-periodic fashion in the order H-H 3, 2, 1, alternating between north and south polar ejections. Moreover, the position angles of the ejections appear to have changed with time (316° for H-H 3, 145° for H-H 2, and 334° for H-H 1), suggesting that the axis of ejection may be undergoing precession. Also, there is some evidence that the knots experience deceleration with time. It is not clear that the tangential velocities represent the true physical motion of the material. As a shock wave moves through material which already possesses a substantial velocity component in the same direction as the shock motion, the shock velocity will appear to add to the bulk motion in the appearance of proper motion. That is, a portion of the proper motion could be due to a moving pulse of excitation. In general, however, it can be shown that this cannot be the major component for the velocities observed in H-H 1 and 2, hence one must agree with the conclusion of Herbig and Jones (1981) that the tangential velocities are probably dominated by true physical motion.

Although it is not certain that H-H 3 is associated with the C-S star, its near alignment with H-H 1 and 2 and the possible effect of precession upon the position angles of ejection suggest the association. Without allowing for deceleration effects, one would conclude that H-H 1 was ejected about 230 years ago, and H-H 2 about 1200 years ago. These numbers will be greater if the tangential velocities do not represent true bulk motion, and the times will be less if significant deceleration has occurred. In any case, it appears that the C-S star may have suffered at least three different ejection episodes separated by approximately 1000 years each, with H-H 3 having experienced significant deceleration within the past 1000 years. The conclusion that H-H objects may be ejected periodically along opposite axes is reinforced by the H-H 46-47 system which is also sketched in Figure 13. Unfortunately, proper motion data are not yet available for this system, and the distance assumed (400 pc) is somewhat uncertain since the globule lies in the very distended Gum nebula.

If the idea of quasi-periodic, alternate north and south polar ejections is taken seriously, this presents a challenge to the theory of mass flows from such stars. The behavior might suggest the presence of a "reservoir" which manages to confine a continuous mass loss until the "dam" breaks with a resultant eruption of the stored material, whereupon the cycle may repeat. However, what mechanism could confine an eruption to one direction only? A global eruption in the presence of a circumstellar disk might be expected to produce simultaneous, oppositely directed flows. Are the eruptions hemispheric in nature, perhaps modulated by periodic changes in a strong magnetic field?

Finally, it is interesting to consider the potential consequences of H-H objects as viewed from a galactic perspective. Observations suggest that the objects are typically of order .01 pc in diameter, 10^4 cm^{-3} in density, and with velocities in the range 100 - 400 km s^{-1}. If such objects remain coherent long after they have moved from their stellar nurseries and after their shock wave luminosities have faded, we are faced with the possibility of a relatively large population of such high velocity objects filling the galactic halo. There are two ways of estimating the numbers of such objects. First, the fact that roughly 100 luminous H-H objects are known within a distance of 10^3 pc implies that star-forming regions in the Galaxy currently harbor at least 10^5 luminous H-H objects. The lifetime of a luminous object is probably in the range 10^3 - 10^4 yrs., after which it enters the interstellar field as a cold cloudlet. If the production of H-H nebulae has been constant over a 10^{10} yr. galactic history, the analysis suggests that 10^{11} - 10^{12} high velocity cloudlets may occupy the galaxy. The second method is to assume that most stars in the galaxy will at one time have produced H-H objects (one or more), hence the number of cloudlets should be comparable to the number of stars, a figure which is bracketed by the estimate above.

Because of the random orientations of H-H ejections, the resulting distribution of cloudlets might mimic that of Halo population objects. Thus, at any given time only about 1%, or 10^9 - 10^{10} such relict H-H cloudlets, would occupy the galactic disk. Such objects would make their presence known only if they encountered a medium of sufficient density to rekindle a luminous shock wave. The number density of such objects in the disk (assuming a disk thickness of 300 pc and a radius of 1.5×10^4 pc) would then be .005 - .05 pc^{-3}. There may be two possible manifestations of such objects. First, the quasi-stationary floculli seen in the structure of supernova remnant shock waves suggests that the knots are inherent to the structure of the interstellar medium. Could the knots be re-kindled H-H cloudlets? Second, there are a number of H-H objects for which no exciting stars have been identified. Could relict H-H cloudlets, plunging into a molecular cloud complex, account for such objects? Of course, whether such a population of relict cloudlets exists depends ultimately upon whether such objects would remain stable over a galactic lifetime. It seems likely that repeated encounters with disk material would sooner or latter destroy the cloudlets. It is possible that some of the cloudlets will quickly diffuse into the interstellar medium if their internal pressure is too great to remain in equilibrium with the interstellar medium. That this may occur is suggested in the cases of H-H 7-11 and H-H 43, 38 where the more distant the H-H nebula is from the exciting star, the more diffuse the nebula appears.

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DISCUSSION

S. Strom: The idea for HH 1-2 of a collimated flow which precesses on time scales of several hundred years appears confirmed from our monochromatic photograph of HH 12 and surroundings. Here, the Hα photograph suggests *continuous*, collimated outflow with precession time scales of several hundred years.

R. Schwartz: For HH 1,2,3 the precession time scale would be more like thousands of years, although this is very difficult to judge from only 3 data points.

S. Strom: The T Tau nebula situation appears to be a model for many HH-objects. The HH nebulae in our recent monochromatic photographs also show shock-excited gas *interior* to reflection nebulae -as if the shock region maps that part of the cloud which has been (or is being) cleared out by the wind thereby allowing light from the star to reach the edge of the cavity producing a reflection nebula.

R. Schwartz: Yes, and Hind's nebula at T Tauri reinforces this notion by its arcuate and somewhat "layered" appearance, suggesting that it is cool, post-shock material which is now visible by virtue of its dust content and its proximity to T Tau which results in a reflection nebula.

Ambartsumian: You have used the term ejection of HH-objects from T Tauri stars. Do you mean now that the objects are really ejected from the surface of exciting stars or they merely are only accelerated cloudlets of ambient material?

R. Schwartz: The term "ejected" is used mainly to describe the appearance of proper motions and large radial velocities in the objects. We still do not have a very clear picture of where the material originates and how it is organized into collimated flows.

Montmerle: Could you comment on the possible detection of HH 1 in X-rays (Einstein Satellite) by Pravdo *et al.*?

R. Schwartz: The X-ray beam was relatively large and included the C-S star which very well might be an X-ray source like other T Tauri stars. However, given the fact that a fairly high temperature ($\sim 3\times10^5$ K) region is required in HH 1 to produce C IV, etc. in the *UV*, perhaps we should not dismiss too quickly the possibility that a spot in the object might be hot enough to produce soft X-rays.

Lada: Could you comment on the energy budget of HH-objects? Can you account for these luminosities in your models?

R. Schwartz: This is a fundamental question, the answer to which bears upon the origin of HH's. For HH 1 the total radiative output (optical + *UV*) is of the order of 1 $L_\odot$, whereas its presumed exciting star (the C-S star) has $L \sim 20\ L_\odot$. It is difficult to see how a star of relative low luminosity could maintain a steady-state flow with sufficient mechanical energy to excite HH 1 and 2 to their observed luminosities. I think that this points to an impulsive event (or series of events) in the star which gave rise to the HH's.

Mundt: (*Comment*) I have recently obtained deep CCD images of the HH 1, 2 area (filter λλ6200, 7000 Å). This image indicates the presence of two "cones of nebulosity" pointing away in opposite directions from the center between HH 1 and HH 2 (and not from the C-S star). This suggests that the C-S star is not the exciting star but there might be a highly obscured star roughly located in the center between HH 1 and HH 2.

R. Schwartz: Cohen and I have been unable to detect any 2.2μm sources other than the C-S star between HH 1 and 2, and we gave special attention to what may be the feature you suggest, a very faint nebulosity, about 30" SE of HH 1. My 4-m plates taken in Hα and [S II] light suggest that this feature may be a very low-excitation, low surface brightness HH nebula.

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