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50 YEARS OF HERBIG-HARO RESEARCH

From discovery to HST

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Abstract. We review the events leading to the discovery of Herbig-Haro objects half a century ago, and the early efforts to understand the nature of these enigmatic objects. The recognition in the mid-seventies of the shocked nature of HH objects heralded a burst of observational and theoretical efforts, and further impetus was soon after provided by the discovery of high proper motions, and by detailed optical, infrared and ultraviolet spectroscopic studies. The recognition in the early eighties of HH jets was the starting point for the increasingly intense studies during the last 15 years which we discuss in this Symposium. In the second half of our review, we summarize the insights into the nature of HH jets provided by analyzing high resolution images obtained with the *Hubble Space Telescope* of two of the finest known HH jets, HH 47 and HH 111.

1. The Discovery of HH Objects

The first example of what we now call Herbig-Haro objects was seen more than a century ago, when Burnham (1890, 1894) looked with the naked eye through the Lick Observatory 36-inch refractor towards T Tauri and saw the faint glimmer of what has come to be known as Burnham's Nebula, or HH 255. The matter rested there for another half century until in the late forties George Herbig and Guillermo Haro independently discovered some curious semi-stellar objects in Orion. A series of four brief papers resulted, which uncovered the basic properties of these objects. In 1950, Herbig drew attention to the peculiar spectrum of Burnham's Nebula with its strong emission lines of [S II], [O II] and H (Herbig, 1950). This was followed in 1951 by another paper in which Herbig presented a photograph of HH 1, 2 and 3, and noted their spectral similarity to Burnham's Nebula (Herbig, 1951). In 1952 and 1953, Haro presented the discovery of several more objects, and noted that they were invisible on "infrared" plates. Herbig had postulated the existence of either faint blue high-temperature stars or late-type dwarfs inside the HH objects, and Haro concluded from his observations that if the stars were cool he should have detected them (Haro, 1952, 1953). Ambartsumian (1954,1957) suggested that these peculiar nebulous objects, which he called Herbig-Haro objects, might represent the early stages of newly formed T Tauri stars, based on their co-existence with nearby nebulous or emission-line stars (e.g. Herbig, 1946, Haro, 1950).

We have asked George Herbig to describe the circumstances of discovery of HH objects, and he has kindly sent us the following:

> *To the best of my recollection, and without going through all my early records and correspondence, it went about like this. While looking around for new T Tauri stars as part of my thesis, I ran across BD -6° 1253 (now V380 Ori), which illuminates NGC 1999. A note on this was published in PASP in 1946. In 1946-47, I took some direct photographs of the region of NGC 1999 with the Crossley reflector at Lick, and noticed some odd little fuzzy blobs nearby; these later became HH-1, -2 and -3. According to my notes, the first such plate was taken on 1946 Jan 24, followed by 2 others in Jan. and Feb. 1946. I have among my papers only an enlargement of a plate taken the next year, Jan. 20, 1947, with the same telescope and exposure time. This shows the 3 HHs.*
>
> *I paid no serious attention to these Objects at the time, but in December 1949 I met Haro at the AAS meeting in Tucson. He gave a paper on his objective-prism discoveries of emission-H-alpha stars around the Orion Nebula, an abstract of which appeared in AJ in 1950, and called attention to the emission-line spectra of these Objects near NGC 1999. He published details later in ApJ in 1952 and 1953. This re-ignited my interest in these spectra, because during the winter of 1948-49 at McDonald I had obtained spectra of Burnham's Nebula at T Tauri, which had the same odd combination of emission lines including [S II] and [O II]; a paper on this appeared in ApJ in 1950.*
>
> *So at Lick in 1950, I obtained slit spectra of HH-1 and -2, from which came the note in ApJ in 1951, in which attention was drawn to the similarity to Burnham's Nebula. It was probably this connection with T Tauri that gave rise to the conjecture that Herbig-Haro Objects, as they were named by Ambartsumian, had something to do with early stages of star formation.*

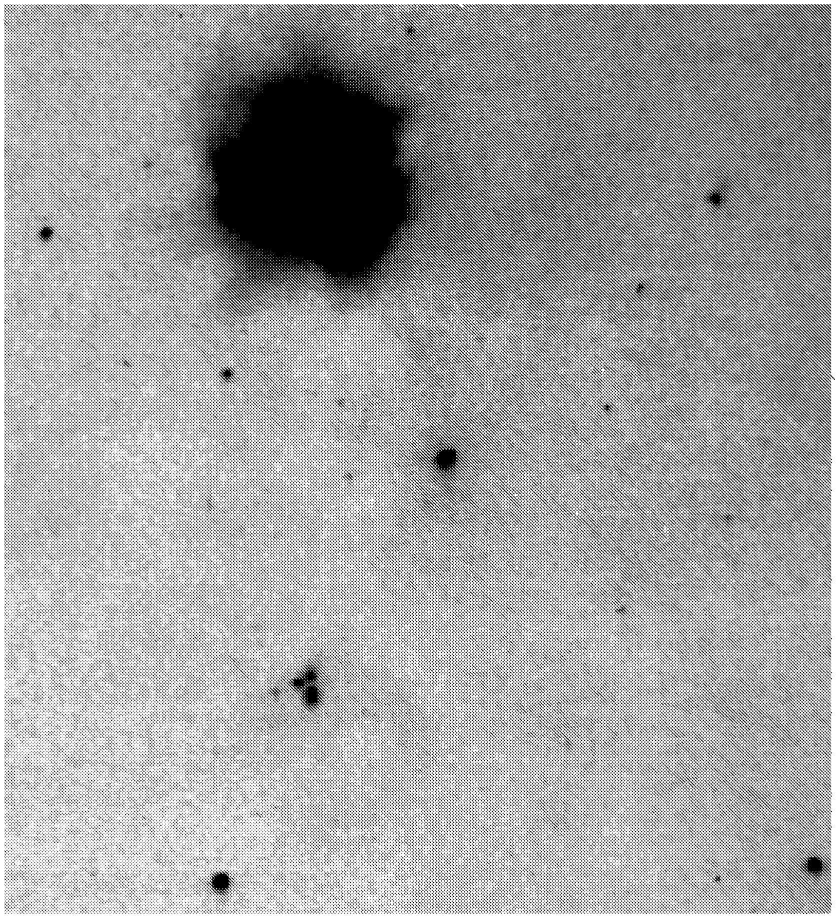

Figure 1. HH 1, 2 and 3 as seen in an enlargement of the Jan 20, 1947 plate which was published in Herbig (1951). The plate was taken in the blue spectral region with the Crossley reflector at Lick Observatory. Courtesy George Herbig.

In Figure 1 we show the Jan. 20, 1947 plate of Herbig, which appeared in his 1950 paper. As our present IAU Symposium started on Jan. 20, 1997, we were thus able to celebrate the 50th anniversary of this first published photograph of HH objects.

2. The Early Years

In 1956, Karl-Heinz Böhm published his spectrophotometric analysis of HH 1, and concluded that the nebula was non-uniform with a mean electron temperature of $T_e = 7500$ K and electron densities between a few times $10^3 cm^{-3}$ to a few times $10^4 cm^{-3}$. In the absence of any known energy source and faced with the relatively high ionization levels observed, Böhm speculated that a low luminosity hot star could be hidden in the nebular condensation. Hoyle (1956), on the other hand, argued that one should not exclude accretion energy as the source of excitation.

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In 1958, a short paper appeared by Don Osterbrock in which he argues against photoionization from a hot source inside the HH objects. In the case of Burnham's Nebula he suggested that, as already surmised by Herbig in his two discovery papers, high velocity mass loss ejectae from T Tauri might deposit energy in the nearby nebula. Magnan & Schatzman (1965) proposed that even more energetic protons (100 MeV) hitting a neutral medium could produce the observed ionization.

Haro & Minkowski (1960) demonstrated, based on new and deeper plate material, that no star down to very faint limits could hide in the HH nebulae and argued that the condensations might contain protostars.

An important observational fact about HH objects, namely their variability, was documented by Herbig (1957, 1958, 1968, 1973), who showed that individual HH knots could gradually fade or brighten on timescales of a few years, and new ones could even appear.

Herbig (1974) compiled a list of all HH objects known up to then, a total of 43 objects. For comparison, the latest listing contains about four hundred HH objects (Reipurth, 1997), and new objects are discovered all the time.

3. Shock Physics, Kinematics and Multi-Wavelength Data

After the relative hiatus of the sixties, Herbig-Haro research experienced a true avalanche of papers in the mid-seventies, and only a small number of key studies, especially observational ones, can be mentioned here.

An important discovery was made by Strom *et al.* (1974a), when they detected an embedded infrared source displaced from HH 100 in the dark clouds of Corona Australis. This led to the proposal that HH objects are small patches of reflected light projected onto cloud material through cavities around deeply embedded newborn stars (Strom *et al.*, 1974b).

An alternative model, which had a dramatic effect on Herbig-Haro research, appeared in 1975, when Dick Schwartz proposed that a supersonic stellar wind from T Tauri would create radiating shocks where the flow encounters the ambient medium. The basis for this idea was the observation of lines with supersonic radial velocities around T Tauri, and the similarity of HH spectra to those of certain supernova remnants.

In 1978, three papers appeared which came to have a profound influence on our way of thinking of HH objects.

Dick Schwartz elaborated on his shock interpretation, and proposed a more specific model in which small cloudlets are run over by strong stellar winds from T Tauri stars. In this way stationary shocks are formed on the side towards the star (Schwartz, 1978).

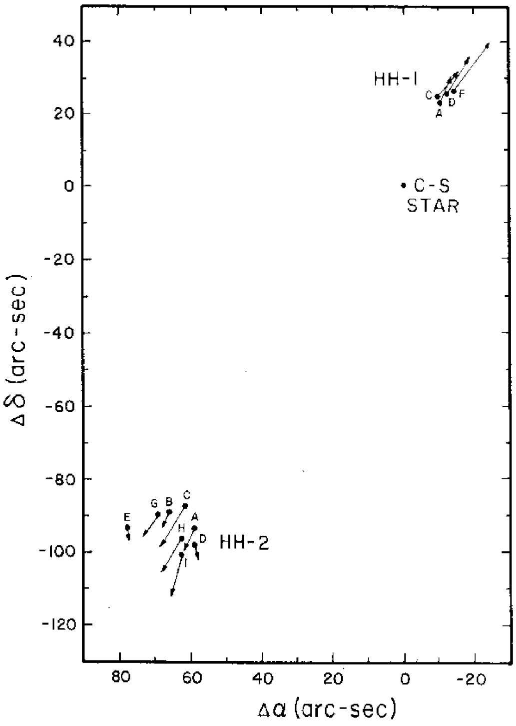

Figure 2. Proper motions of HH 1 and 2, after Herbig & Jones (1981). The Cohen-Schwartz star was earlier thought to be the driving source of the HH complex (Cohen & Schwartz 1979) until the discovery of the VLA source midway between the two HH objects by Pravdo *et al.*(1985).

Karl-Heinz Böhm noted that there are two possibilities for creating such shocks, the quasi-stationary shocks of Schwartz, and alternatively running shocks, similar to blast waves. He demonstrated that the time scales of variability, and the sizes, radial velocities and small filling factors of individual knots could be understood in terms of such shocks (Böhm, 1978).

Finally, Mike Dopita presented a large compilation of spectrophotometry of many HH objects, and a comparison with shock models. In the case of the HH 46/47 objects, he noted a discrepancy between the large radial velocities observed and the lack of [OIII] emission, which implied much lower shock velocities. He concluded that the HH objects were moving into a co-moving medium, and suggested that their sources would be eruptive, similar to FU Orionis eruptions (Dopita, 1978a).

In 1979, Gary Schmidt & Joe Miller published their spectropolarimetry of HH 24, an object known for its large polarization. They concluded that the emission lines are unpolarized, while it is the continuum that is responsible for the observed polarization. This is consistent with the lines forming in shock waves, and the continuum being due to reflected light. The dispute over models was thus closed in favor of the shock model.

Two papers appeared in 1979 and 1981 by Cudworth & Herbig and by Herbig & Jones which had a tremendous impact on the field. In these papers it was established that HH 28/29 and HH 1/2 have very large proper motions of the order of several hundred km/sec. Figure 2 shows the proper motion vectors of HH 1 and 2 from Herbig & Jones (1981),which established the bipolar nature of these objects. In those days the Cohen-Schwartz star was assumed to be responsible for these HH objects (Cohen & Schwartz, 1979), and only later was the central VLA source discovered (Pravdo *et al.*, 1985). For those who have entered the field of HH research within the last 15 years it is perhaps difficult now to imagine the profound effect this figure had on us then. As a curiosity it can be mentioned that the large proper motions of HH 28/29 was noted already back in 1963 by Luyten, who assumed that they were faint red stars.

1980 was the year when unexpected spectroscopic characteristics of HH objects were discovered.

First, Böhm and collaborators drew attention to some rare low excitation HH objects with peculiar line ratios, including very strong forbidden S II lines. These objects could not be explained by the shock models employed in those days, a first sign that plane-parallel shock models were inadequate for dealing with HH objects, thus anticipating the need for bow shock models (Böhm *et al.*, 1980).

1980 was also the year when Jay Elias published his important paper on the detection of molecular hydrogen emission lines by infrared spectroscopy of a number of HH objects. Already in this early paper he pointed out that the shocks producing these H_2 lines could have shock velocities of not more than 20 km/sec, and that this was discrepant with the shock velocities determined from optical lines and plane-parallel models (Elias, 1980).

At the other side of the visible spectrum, Ortolani & D'Odorico (1980) published their ultraviolet spectrum of HH 1 between 1000 and 2000 Å, showing a surprisingly strong UV continuum and emission lines. In a more detailed study shortly afterwards, Böhm *et al.* (1981) noted that HH 1 emits about 20 times more energy in the ultraviolet than in the whole visible range, and pointed out the inadequacy of the then existing shock models to account for the lines detected of very high ionization, like for example C IV.

During the early eighties, the locations and properties of the energy sources of HH objects were gradually established. As an example, L1551 IRS 5, which had been discovered at near-infrared wavelengths by Strom *et al.* (1976), was detected at two far-infrared wavelengths in a balloon-borne experiment by Fridlund *et al.* (1980), who thus derived a total luminosity of this HH source of 25 $L_\odot$ and documented the importance of cold circumstellar dust emission. In a large study, Cohen & Schwartz (1983) surveyed the surroundings of numerous HH objects at near-infrared wavelengths and detected many of the sources with which we are today familiar.

In 1980, Snell, Loren and Plambeck published what is certainly among the most cited papers related to low mass star formation, namely their discovery of the bipolar molecular outflow emanating from L1551 IRS 5, and the presence of HH 28 and 29 in the blue lobe. The relation of HH objects to molecular outflows has become a vital field of research, and is discussed in detail by Cabrit *et al.* and Padman *et al.* elsewhere in this volume.

And now we finally get to the jets. As early as 1978, Bart Bok published an excellent photograph of the HH 46/47 objects in a globule in the Gum Nebula. But it was not until the spectroscopic work of Dopita *et al.* (1982) and Graham & Elias (1983) that it was established as a fine bipolar HH complex, and indeed Dopita *et al.* (1982) realized that the HH 46/47 objects form a bipolar jet emanating from a newborn star. The following year, Mundt & Fried published their highly influential paper about jets from young stars, in which they presented the discovery of four HH jets. This quickly lead to the idea that many, perhaps most, HH objects might be a manifestation of highly collimated outflows.

This is approximately where we stood at the time of the first Herbig-Haro symposium in Mexico City in 1983. This second symposium devoted to Herbig-Haro flows and their relation to star formation documents the enormous advances which the field has experienced in the intervening 14 years. We cannot even begin, in the limited space available, to summarize the enormous body of observational and theoretical work which has been done during this period. Instead, in the remainder of this review, we will focus on what has been learned about two of the best studied HH jets, HH 111 and HH 46/47. One of the most exciting recent developments has been the availability of extremely high resolution images of these and other jets obtained with the *Hubble Space Telescope* and we will place especial emphasis on what such images have to tell us about the nature of HH flows.

4. The HH 111 Jet

The HH 111 jet, together with the very similar HH 34 jet, is the object which comes closest to the text book idealization of how a jet should look. Consequently, it has been the subject of intensive study using the full gamut of observational techniques and has become one of the favorite bench marks against which theoreticians test their models.

The HH 111 outflow is driven by a young star deeply embedded within a compact molecular core in the L 1617 cloud complex in Orion (Reipurth, 1989). In ground based images (see Figure 3) the jet appears as a bony

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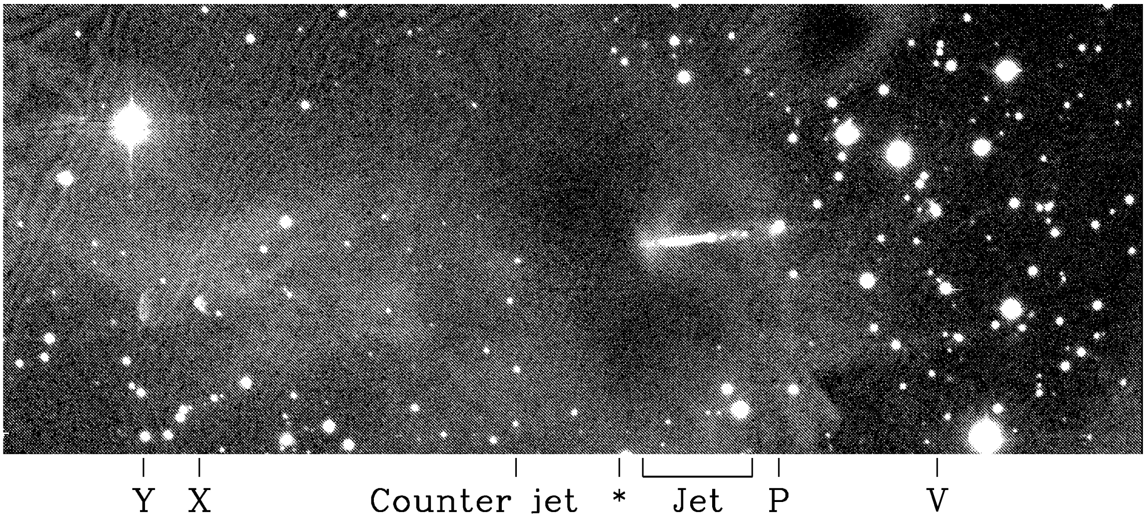

Figure 3. The HH 111 complex as seen on a Gunn-r CCD image obtained at the ESO 3.6m telescope.

finger pointing away from the location of the (optically invisible) source towards an outlying bow shock HH 111V. The jet and V are both blue shifted. Proper motion and radial velocity measurements show that they recede from the source with a space velocity of about 400 $\mathrm{km\,s^{-1}}$ and that the flow is inclined at an angle of only 10° to the plane of the sky (Reipurth *et al.*, 1992). On the opposite side of the source from V, a counter jet and a pair of bow shocks, HH 111 X and Y, trace the red shifted lobe of the outflow. At optical wavelengths the counter jet is highly obscured and consequently faint. However, infrared observations show that the two sides of the flow are in reality highly symmetric (Gredel & Reipurth, 1994).

The most violent action in a jet should occur at the "working surface" where the supersonic flow slams into the surrounding gas, so it is natural to identify high excitation, bow shaped objects like HH 111V with such crash sites. In Figure 4 we give a close up view of this feature obtained using the WFPC2 imager on *HST* (Reipurth *et al.*, 1997a). This object should consist of two shocks, a "reverse shock" (or Mach disk) which decelerates the fast moving jet gas and a "forward shock" (or bow shock) which accelerates the ambient material. At the spatial resolution of *HST* (a WFPC2 pixel subtends 46 AU or 1.5×10^{13} cm at the distance of HH 111) it is possible, for the first time, to resolve the cooling zone behind these radiative shocks and examine their structure.

In the Hα image (Figure 4a), the brightest emission comes from an unresolved filament which wraps around the leading edge of knot V. A broader arc of [S II] bright material runs parallel to this Hα rim, but is displaced $0\farcs5$ (230 AU) closer to the source (Fig. 4b). This stratification, already detected in ground-based images (Reipurth *et al.*, 1992), is especially clear in

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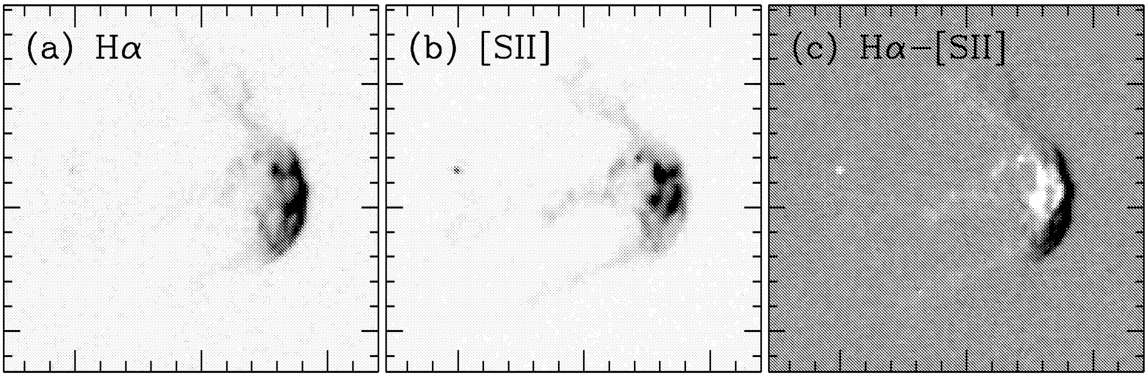

Figure 4. A detailed view of the HH 111V working surface as seen with *HST*: (a) Hα; (b) [S II]; and (c) an Hα – [S II] difference image in which Hα-bright regions are shown in black and [S II]-bright regions in white.

Fig. 4c which shows the result of subtracting the [S II] image from the Hα image. The region enclosed by these leading arcs has a complex structure of clumps and filaments with characteristic sizes of 100-250 AU.

The leading Hα bright filament traces the layer immediately following the "forward shock" where neutral hydrogen atoms are collisionally excited giving rise to strong Balmer emission (Chevalier & Raymond, 1978; Heathcote *et al.*, 1996). This thin skin of collisionally excited Hα wraps around the apex of the bow shock and appears as a bright rim where the line of sight runs tangent to its surface. Hα filaments seen projected against the core of knot V probably arise where corrugations in the surface of the shock front bring it close to the line of sight. The arc of [S II] emission behind the shock front arises in the extended cooling zone where gas heated by passage through the "forward shock" cools and recombines emitting strong forbidden lines of various metals as well as recombination lines of hydrogen. The clumped structure of this region may result from instabilities in the cooling flow. There is no obvious Balmer filament which might delineate the "reverse shock" so its location is less clear. Some of the condensations in the interior of HH 111V emit both [S II] and Hα and are probably material cooling behind the bow shock. Others have strong [S II] emission but little Hα and are probably shocked jet material.

The spectrum of HH 111V presents us with the same puzzle faced by Dopita (1978b) in the case of HH 46/47. Although the space velocity of V is $\sim 400\ \mathrm{km\,s^{-1}}$ no [O III] emission is detected implying that the shock velocity must be $< 100\ \mathrm{km\,s^{-1}}$. These facts can only be reconciled if HH 111V advances into gas which is flowing away from the driving source at high velocity. Comparison between the observed two dimensional velocity field of V and that predicted by bow shock models also suggests that the pre-shock medium moves outward from the source at $300\ \mathrm{km\,s^{-1}}$ (Morse *et al.*, 1993a). This implies that, rather than being the terminal shock of the

HH 111 flow, V is an internal working surface, following in the wake of material ejected earlier. Indeed Reipurth *et al.* (1997b) have demonstrated that the driving source is bracketed by two more distant working surfaces, HH 113 and HH 311, so that in Figure 3 we are only seeing the core of a giant outflow with a total extent of more than 7 pc! The HH 111 complex is only one of several cases where multiple working surfaces are found within a single outflow, confirming the idea first suggested by Dopita (1978b) that the mass loss from new born stars is episodic with major eruptions occurring on time scales of a few centuries.

From the moment of their recognition, HH jets have posed a difficult conundrum; how to account for their characteristic low excitation spectra, indicative of a shock velocity of at most several tens of $\mathrm{km\,s^{-1}}$, in face of their supersonic space velocities of several hundred $\mathrm{km\,s^{-1}}$. Two competing explanations have been advanced. On the one hand, Ray *et al.* (1988) proposed that Kelvin-Helmholtz instabilities at the boundary of the jet beam could excite oblique (hence weak) shocks within it, which would appear as low excitation emission knots. Various observations of jets have been interpreted in the framework of this model (Bührke *et al.*, 1988; Eislöffel & Mundt, 1992). On the other hand, Dopita (1978b) and Reipurth (1989) have argued that jets are highly transient, intermittent events driven by eruptions of their driving sources. Variations in the velocity of the flow would generate internal working surfaces propagating along the jet and having shock strengths comparable to the amplitude of the velocity perturbation (Raga *et al.*, 1990; Stone & Norman, 1993). Observations of knots in jets have been interpreted in light of this model by several authors (e.g. Heathcote & Reipurth, 1992; Reipurth *et al.*, 1992; Morse *et al.*, 1993b).

These two models predict very different internal structures for the knots, which can easily be distinguished at the spatial resolution of *HST*. Fig. 5 provides a detailed view of the bright section of the HH 111 jet (Reipurth *et al.*, 1997a) which is seen to consist of a chain of well resolved knots embedded in a diffuse, gently wiggling sheath of faint [S II] emission. The bright knot L at the tip of the jet is very obviously an internal working surface having a morphology similar to that of V. This result was foreshadowed by the ground based images of Reipurth *et al.* (1992). Further support for this interpretation comes from the fact that this knot has a large velocity dispersion comparable to that of V (Reipurth *et al.*, 1997a) and additionally shows weak [O III] emission (Morse *et al.*, 1993b) implying that it has a shock velocity higher than that of V. Most of the other bright knots in the jet also have clear bow shock shapes. Some are centered on the axis of the jet and form complete arcs with wings swept back symmetrically on both sides, while others are displaced slightly from the axis of the jet and are one-sided with a trailing wing on the "outside" of the jet. Typically these

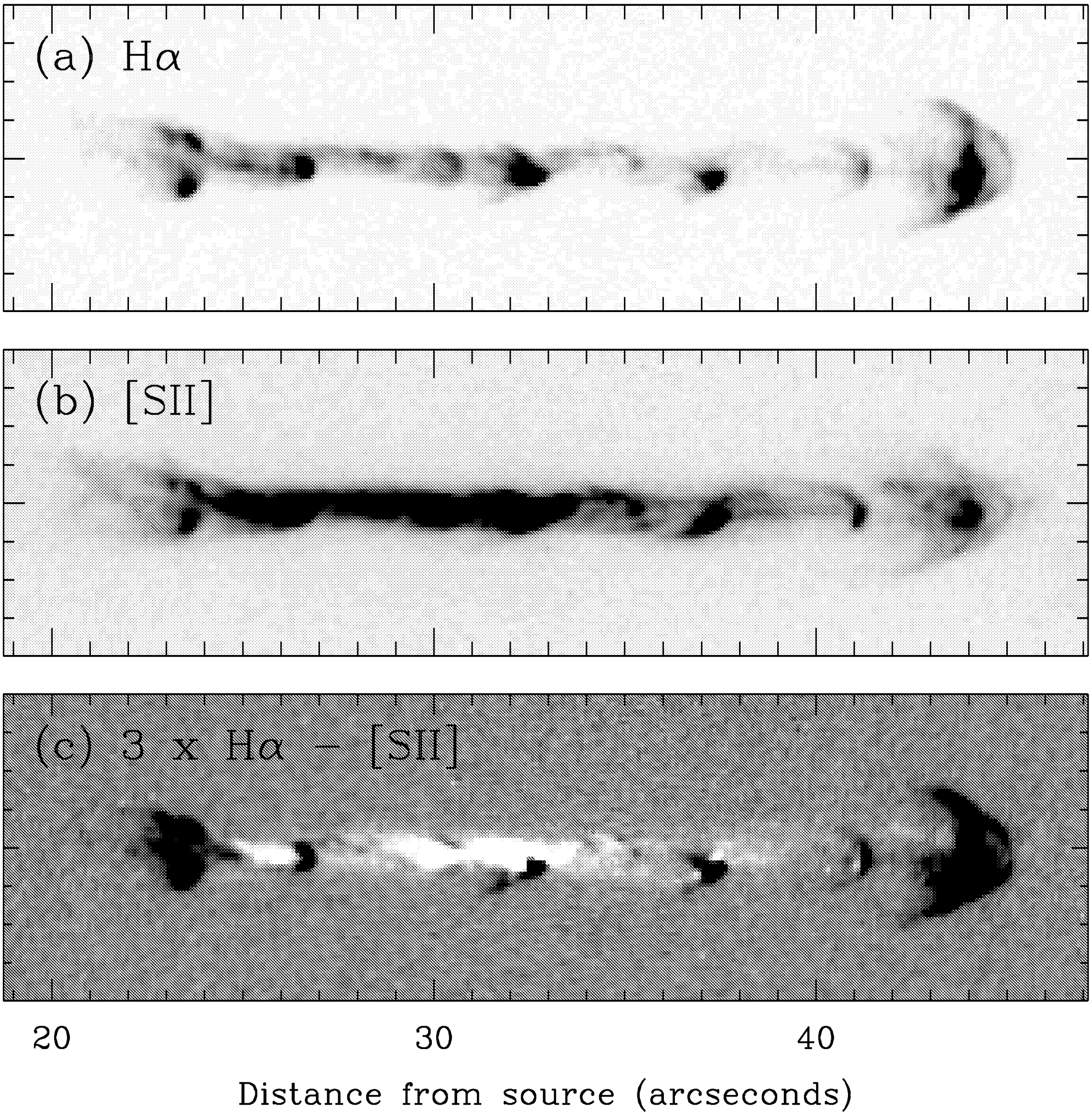

Figure 5. *HST* images of the HH 111 jet: (a) Hα; (b) [S II]; and (c) 3×Hα – [S II].

knots show the same kind of excitation stratification as HH 111V with an Hα filament wrapped around a [S II] bright core. This morphology strongly suggests that, at least in the HH 111 jet, the knots are internal working surfaces caused by variations in the ejection velocity of the jet. If a new impulse emerges precisely along the axis of the jet, then we see a symmetrical bow, whereas if the ejection occurs at a slight angle to the axis of the jet a one-sided feature results. The leading Hα arcs mark the shock front while the [S II] emission arises in the post-shock cooling zone. The spacing of the knots and the proper motion of the jet imply that the internal working surfaces are the result of eruptions which occur at intervals of a few decades.

The HH 111 complex is associated with a molecular outflow (Reipurth & Olberg 1991, see also Cernicharo *et al.*, this volume). High spatial resolution millimeter-wave interferometric data show that the low velocity molecular gas is unusually well collimated and has the form of a cylinder surrounding the HH jet (Cernicharo *et al.*, 1997). This system thus provides the perhaps most persuasive example of a molecular flow driven by an HH jet. The extended wings of a bow shock are effective in sweeping up and accelerating the ambient gas. Thus the passage of a succession of internal working surfaces along the jet could well, over the course of time, have dragged material from the dense molecular core to form the observed CO flow. The wings of the faint bow shocks beyond knot L have a lateral extent comparable to the radius of the molecular cylinder, and may interact with, and be confined by the molecular gas. In addition to the slow molecular flow, Cernicharo & Reipurth (1996) also discovered several high velocity CO bullets in the gap between the tip of the jet and HH 111V and in the region beyond it. These bullets have space velocities of 400-500 $\mathrm{km\,s^{-1}}$ comparable to that of the jet. They are thus unlikely to be entrained material, but rather must be jet material ejected from the driving source. Infrared observations also reveal H_2 knots embedded in the working surfaces L and V (Gredel & Reipurth, 1994). Thus the bullets are probably dense material trapped and squeezed between the radiative shocks in the working surfaces which has cooled sufficiently to form molecules.

5. The HH 47 Jet

Next we turn to HH 46/47, the object which got the entire HH jet bandwagon rolling (Dopita *et al.*, 1982). It emanates from an isolated Bok globule which harbors a highly obscured infrared source. The flow is bipolar with the northeastern lobe approaching us and the southwestern lobe receding. The HH 47 jet itself, located in the approaching lobe, emerges from a reflection nebula illuminated by the hidden source and terminates in the bright bow shock HH 47A. The jet is surrounded by an elongated bubble of faint shock excited emission, HH 47D. In Hα and [S II] only a cap of this bubble is visible. However, in [O II] the wings of HH 47D extend all the way back to the reflection nebula completely enclosing the jet (Hartigan *et al.*, 1990). In the optical, the receding lobe is traced by a faint stubby counter jet which points towards a short arc of emission HH 47C. However, as in the case of HH 111 this asymmetry is in large part the result of overlying obscuration. In the infrared, HH 47C is seen to mark the apex of a complete bubble of H_2 emission very similar to HH 47D (Eislöffel *et al.*, 1994). The total extent of the complex from HH 47D to HH 47C is about 0.57pc. Combining the radial velocity measurements of Morse *et al.* (1994) with

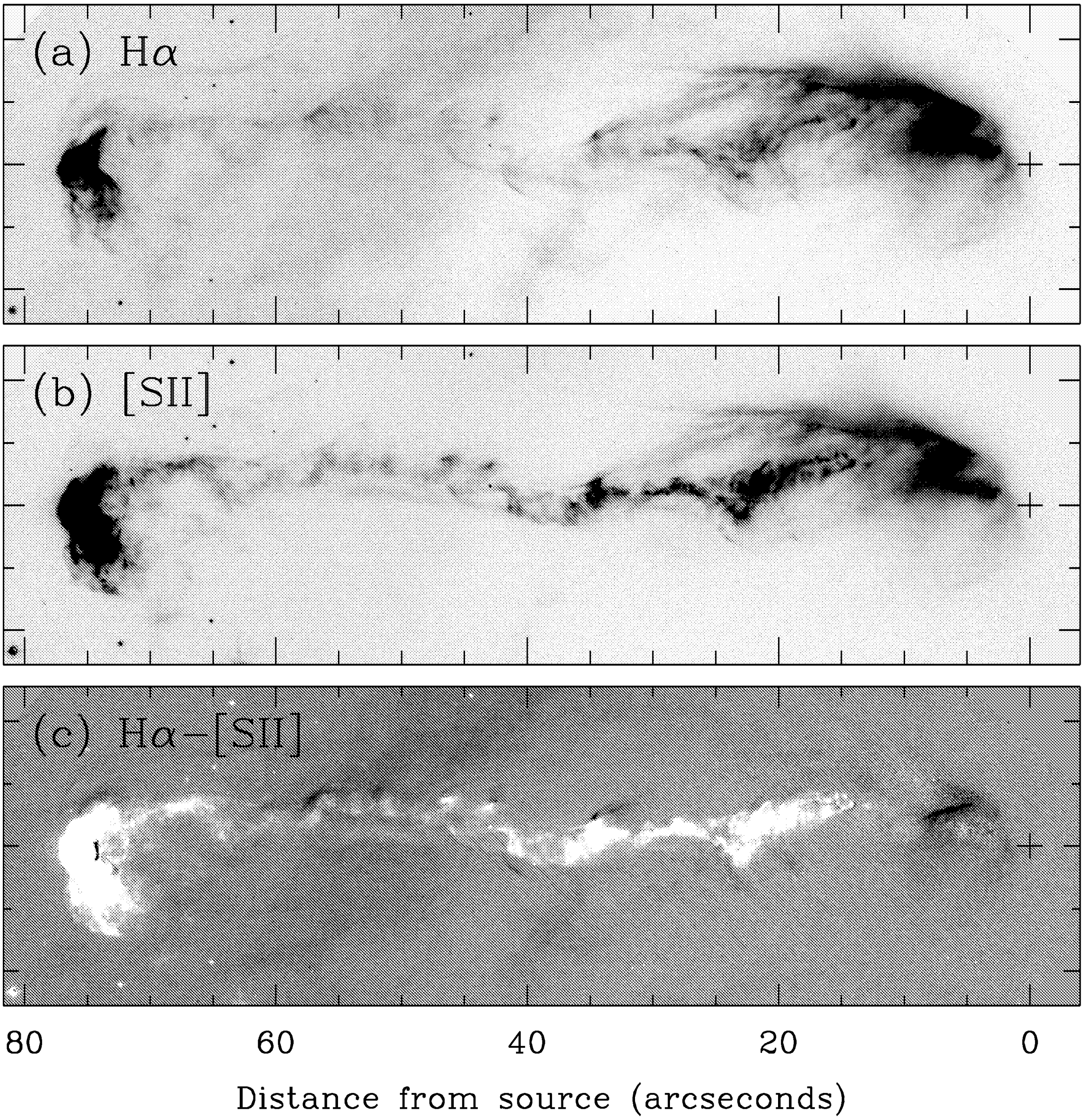

Figure 6. *HST* images of the HH 47 jet: (a) Hα; (b) [S II]; and (c) Hα − [S II].

the proper motions derived by Eislöffel & Mundt (1994), and assuming a distance of 450 pc, one finds that the axis of the flow makes an angle of 28° to the plane of the sky. The jet recedes from the source with a space velocity of $300\ \mathrm{km\,s^{-1}}$, while space velocities of similar magnitude are seen in the counter flow.

In Figure 6 we show the HH 47 jet as seen with *HST*. At first glance, the strongest impression given by these images is the very different appearance of the jet in Hα (Fig. 6a) and [S II] (Fig. 6b). While in [S II] we see a winding chain of bright knots, the Hα frame shows a delicate tracery of narrow filaments. The relationship between these two structures becomes clear in the Hα – [S II] difference image shown in Fig. 6c. Here we see that the [S II]-bright knots delineate the "core" of the jet, while the Hα emission comes predominantly from the zone along the edges of the jet. This segregation of [S II]-bright and Hα-bright material was already apparent in the ground based images of Reipurth & Heathcote (1991). However, the *HST* images reveal the remarkable thinness of the Hα filaments, several of which are unresolved even with *HST*. The most prominent Hα filaments trail behind knots in the core of the jet like the wings of miniature bow shocks. Many of the other knots appear to be cloaked in a thin skin of Hα emission. Especially in [S II], the HH 47 jet shows considerable wiggling with several abrupt changes in direction. Many of the best Hα filaments occur at these apparent bends in the jet, and invariably lie on the "outside" of the corner.

It is very unlikely that the flow truly follows the tortuous path traced out by the [S II] emission. These images only show the gas where it is radiating. Rather, each fluid element in such a highly supersonic flow will move ballistically away from the source. Thus the apparent sinuous structure of the HH 47 jet is most likely the consequence of changes in the *direction* of ejection of the jet where it leaves the source. Again the Hα filaments are the result of collisional excitation at shock fronts and the Balmer arcs serve to mark the location of internal working surfaces in the flow. The knotty structure of the HH 47 jet is thus also the result of variability of the driving source. The very different appearance of the HH 111 and HH 47 jets results from the differing importance of directional variations in the two systems. In the case of HH 111, the amplitude of the directional variations is small so that an almost straight, narrow jet with primarily axially symmetric internal working surfaces result. Conversely, the HH 47 jet has undergone larger changes in the direction of ejection leading to a broader, wiggling and more chaotic jet with predominantly one-sided internal working surfaces. Although on short time scales changes in the ejection direction dominate in the HH 47 jet, the multiple working surfaces found in this flow attest to the occurrence of massive eruptions of the source on time scales of several hundred years.

The ground based Fabry-Perot observations of Hartigan *et al.* (1993) showed that the material at the core of the HH 47 jet moves more rapidly than that at the edges, suggesting that the jet is transferring momentum to the surrounding medium and entraining it. This together with the fact that the Hα/[S II] ratio is greater at the edges of the jet than at its core was initially thought to be evidence for turbulent entrainment (Raymond *et al.*, 1994). Larger Hα/[S II] ratios translate into higher shock velocities, consistent with a turbulent entrainment model in which the strongest shocks should occur in the boundary layer between the jet and the ambient medium. However, at the higher resolution of the *HST* images it is apparent that the edges of the jet emit Hα along several well defined shock fronts rather than in a chaotic boundary layer. This suggests that, instead, entrainment is occurring as the result of the collective effect of a succession of internal working surfaces which sweep up and accelerate the gas along the edges of the jet. The HH 47 flow is also accompanied by a molecular flow (Chernin & Masson, 1991; Olberg *et al.*, 1992). However, this flow is effectively unipolar, with a well developed receding lobe, but only a weak approaching lobe. This is most likely because the approaching lobe of the HH 47 flow advances into the medium outside the dense globule so that there is relatively little material for it to sweep up. The reflection nebula at the base of the jet has a complex filamentary structure with the filaments extending parallel to the jet. This perhaps suggests that, at least near its base, the HH flow is dragging dense dusty material out of the cloud.

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