Herbig-Haro Jets and their Role in Star Formation

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1. Half a Century of Herbig-Haro Research

In the late forties, George Herbig of Lick Observatory and Guillermo Haro from Tonantzintla Observatory, Mexico, independently discovered some curious semi-stellar objects in Orion with unusual emission-line spectra. Although it was early on realised that these mysterious objects were somehow related to star birth, for several decades progress in understanding their nature was slow. A major breakthrough occurred in the mid-seventies when it was realised that the characteristic HH spectra, because of their similarity to certain supernovae spectra, could be understood in terms of shocks. Shortly afterwards, it was discovered that HH objects have major proper motions, with vectors pointing away from very young stars. Finally, in the early eighties, it was realised that some HH objects could take the form of highly collimated jets. With those results the scene was set for an explosion in HH research which has continued unabated till today. Indeed, HH flows are now recognised not only as fascinating astrophysical laboratories involving shock physics and chemistry, hydrodynamics and radiation processes, but it has gradually been realised that HH flows hold essential clues to the birth and early evolution of low-mass stars. A few months ago, an IAU Symposium[1] was held in Chamonix in the French Alps, where a total of 178 researchers from 26 countries met to discuss our present level of understanding of Herbig-Haro flows and their relation to disk accretion events and T Tauri winds and other outflow phenomena like molecular outflows, embedded molecular hydrogen flows and radio jets.

During the 11 years that I have worked for ESO in Chile, I have had the opportunity to use world-class instrumentation in the superb observing conditions of La Silla. As I leave ESO to return to academia, I would like to summarise some of my scientific activities of the recent years. In the following pages I will review the status of HH research, with an unapologetic emphasis on my own interests and results.

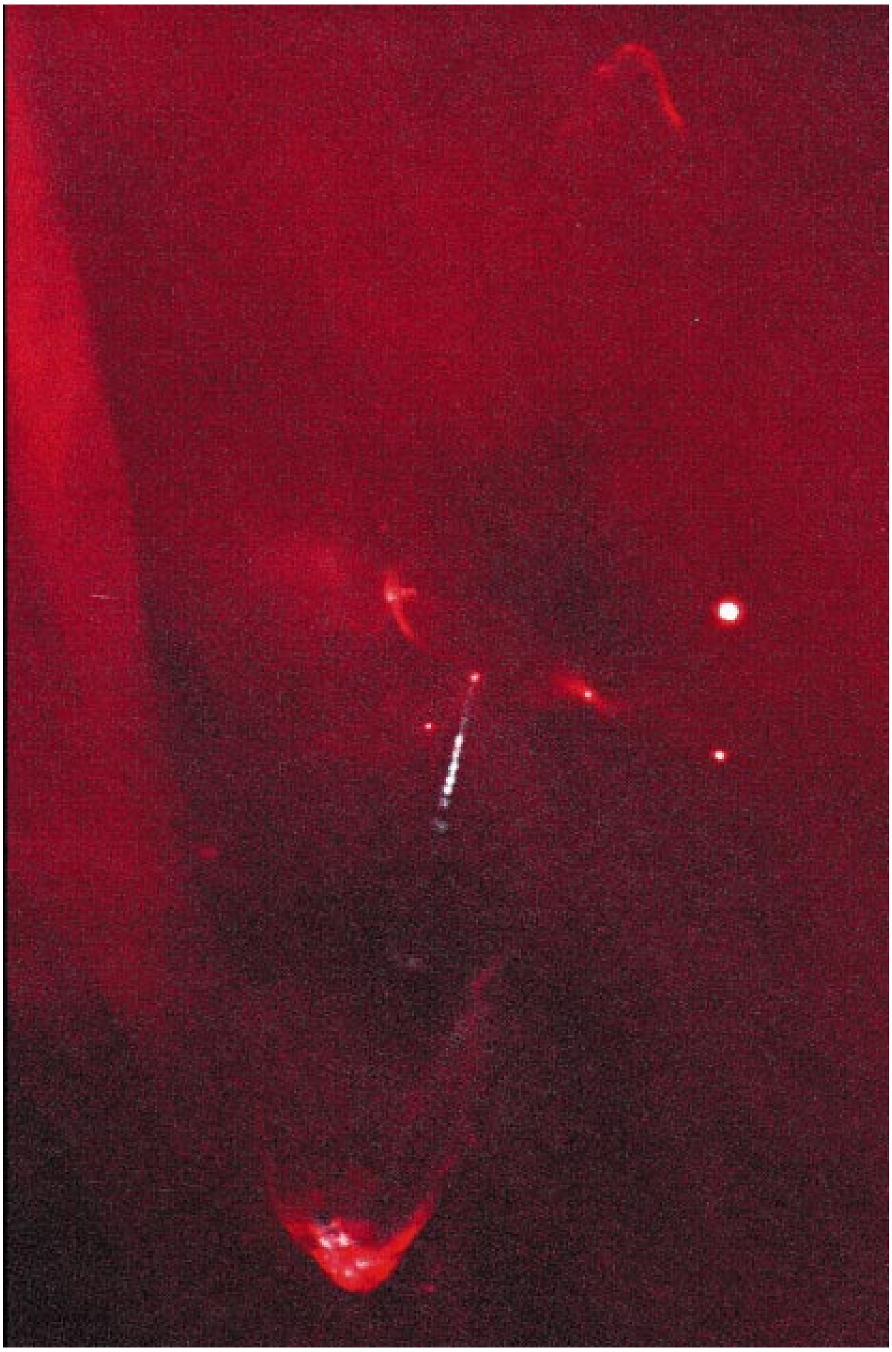

Figure 1: NTT image of the HH 34 jet. Red is Hα strong, and white is [SII] bright.

2. The HH 34 Jet

Figure 1 shows an Hα and [SII] composite CCD image obtained at the NTT, showing the HH 34 jet complex. This jet displays the basic features of HH flows, although rarely are they seen as clean and neatly as in this case. Located in the molecular clouds in Orion at a distance of 460 pc, the jet consists of a chain of compact emission knots which emanate from a faint young star. The jet points straight towards a large bow shock, which marks the point where the supersonic flow rams into the ambient medium. The effect of this ‘working surface’ is to decelerate the fast jet material and to accelerate the ambient medium.

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[1] Herbig-Haro Flows and the Birth of Low Mass Stars, IAU Symposium No. 182, eds. Bo Reipurth and Claude Bertout, Kluwer, in press.

On the opposite side of the driving source and symmetric with the southern bow shock, one finds a fainter counter bow shock. Together the two lobes form a bipolar outflow with an overall extent of 0.4 pc. The southern lobe is approaching us, while the northern recedes. The absence of a collimated counterjet could therefore be ascribed to heavy extinction in the cloud core surrounding the young source, but infrared observations have failed to find evidence for an embedded jet, so it seems likely that the absence of a counterjet is real, a fact that is not easily understood.

Images taken at the NTT on different epochs with several years in between clearly show proper motion in the jet and its bow shock [1]. This way one finds that the flow propagates with a velocity of more than 200 km/sec. When combined with radial velocities determined from long-slit spectra, we find that the flow has an angle of 28 degrees to the plane of the sky.

The particular region of the Orion dark clouds where HH 34 is located is rich in other Herbig-Haro objects, which have been known for some time. A few years ago, it was realised, much to the surprise of the star-formation community, that many of these other HH objects in fact form part of a single giant HH complex, stretching over almost 3 parsecs, and driven by the little faint energy source at the base of the jet [2]. As will be discussed in section 5, the existence of such parsec-scale jets has opened up a discussion about the role of HH jets in creating turbulence and chemically processing the interstellar medium.

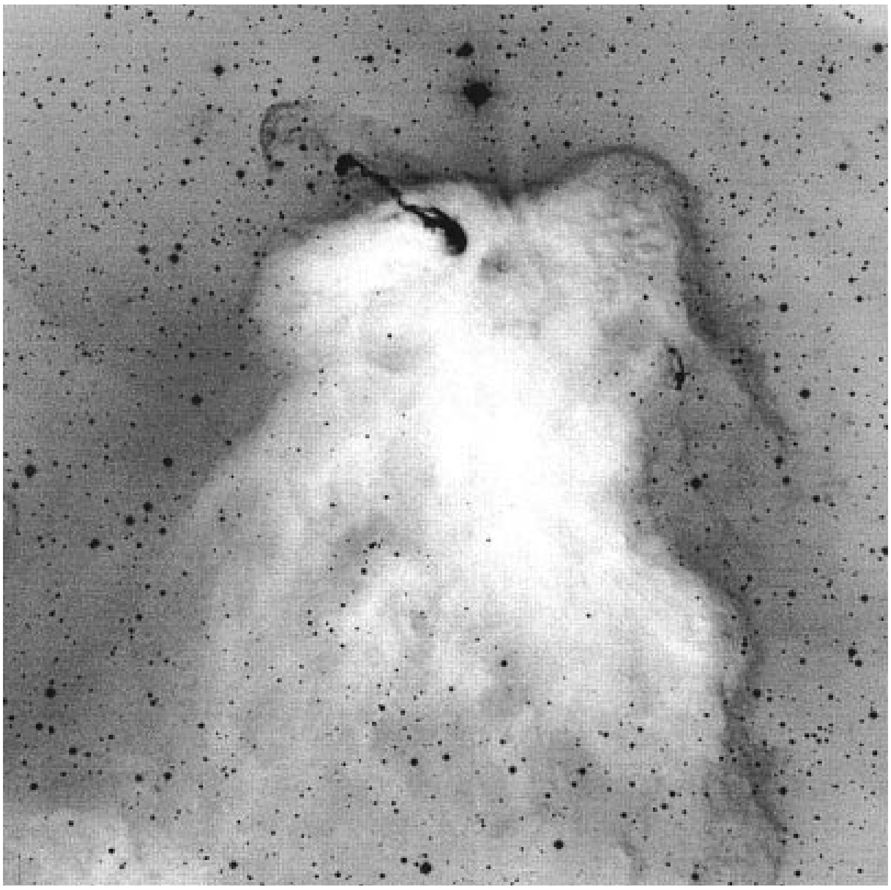

Figure 2: Hα + [SII] NTT image of the HH 47 flow.

3. The HH 47 Jet

The large Gum Nebula in the southern sky is excited by several massive and very luminous stars. The effect of these stars on the pre-existing molecular clouds has been rather devastating, and all over the Gum Nebula one finds windswept cometary globules, which are the remains of larger tenuous cloud complexes that have now been swept away, exposing the surviving denser cloud cores. Sometimes during these violent processes, star formation can be triggered. One such windswept Bok globule with a new-born star inside is seen in an Hα+[SII] image from the NTT in Figure 2. A spectacular bipolar jet, HH 47, is seen to emanate from an embedded young star. Thanks to the efficient removal by the strong UV radiation of the cloud material normally shrouding a cloud core, we here have a view of unprecedented clarity of a bipolar HH jet. The geometry and kinematics of the flow are very similar to the HH 34 flow, and suggest a dynamical age of the system of about a 1000 years [3]. The bright jet is located in the approaching lobe, escaping from the globule, while the red lobe burrows into the interior of the globule, and only a faint heavily obscured counterjet is visible.

The NTT images represent the best that one can do from the ground, so the natural next step was to observe it with the Hubble Space Telescope. We have obtained deep exposures of the HH 47 jet with the HST in Hα and [SII], providing a resolution almost 10 times better than that of the NTT images [4]. Figure 3 shows a colour composite of the main body of the HH 47 jet, with Hα bright regions seen in blue and [SII] bright areas in red. The white curved nebula at the bottom of the jet is a cavity which the jet has dug out of the globule and which is illuminated by the nascent star. Close examination of the image reveals that the jet has two spatially separated components. One is a series of [SII] bright knots, which form the body of the jet, as it winds its way outwards from the globule. Another is an Hα bright fine web of narrow filaments, which are predominantly located at the edges of the jet. It is apparent that the most prominent of these Hα filaments trail behind knots in the body of the jet like the wings of miniature bow shocks, and they often occur at points where the jet shows kinks or shoulders.

It is highly improbable that the jet actually follows the complex path seen in these images. Rather, once the central engine has spewed out a blob of material, it will continue ballistically. Therefore, the winding structure of the jet must reflect a wandering, or irregular precession, of the direction of the ejection axis of the young star. The difference in morphology of the HH 34 jet in Figure 1 and the HH 47 jet in Figure 3 is likely due to a difference in the amplitude of the directional variations of the flow axis: in HH 34 the flow axis is very stable producing a narrow straight jet, whereas in HH 47 the ejection axis roams around producing a wiggling jet.

Fabry-Perot observations of the HH 47 jet reveals that the outer cocoon of the jet body flows slower than the inner parts, much as a viscous fluid passes through a tube [5]. This suggests that the jet may be entraining material and is transferring momentum to the ambient medium as it progresses outwards. The HST images reveal that this process occurs through the collective effect of a succession of small internal working surfaces. As they sweep up and accelerate the ambient gas, the surroundings of the jet is set into motion, which we can observe as one of the molecular outflows so commonly found in star-forming molecular clouds.

At the end of the jet we see a major bright bow shock. Here both ambient material and jet material are shocked, mixed and ejected sideways, and similarly to the smaller shocks around the jet body, this helps to set the ambient medium into motion. Examination of the

Figure 3: The HH 47 jet as seen with HST. Red is [SII] strong, and blue/green is Hα bright.

ratios and profiles of the emission lines emitted from the bow shock tells us about the shock velocity of the material there. When compared to the physical velocity of the bow shock derived from proper motions and radial velocities, one finds that the material velocity is much higher than the shock velocity. This can only be understood if the jet is moving into a medium that has already been set in motion by the previous passage of one or more earlier bow shocks. As can be seen in the wider field image in Figure 2, a large faint bow shock is indeed visible further out on the flow axis.

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 idealisation 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 favourite bench marks against which theoreticians test their models.

Figure 4 shows a composite of deep Hα and [SII] images taken with the ESO 3.6-m telescope. The jet emerges from a young star deeply embedded within a compact molecular core in the L 1617 cloud complex in Orion [6]. The jet has a bright body, terminating in a bow shock, followed by a series of fainter bow shocks, until it fades from view, only to appear again in a bright bow shock, called V, located 0.3 pc from the source. 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 km/sec and that the flow is inclined at an angle of only 10 degrees to the plane of the sky [7]. 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

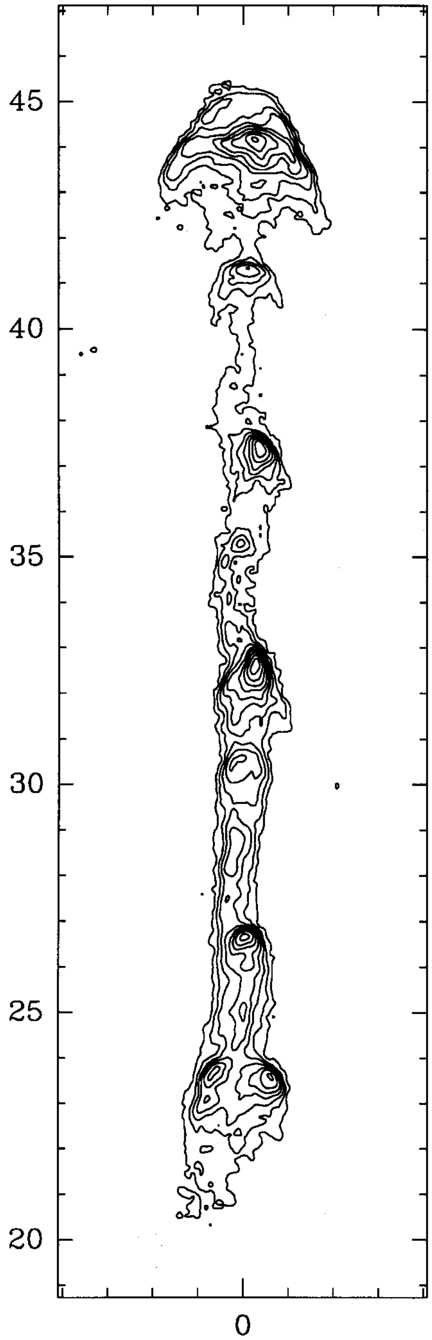

Figure 5: Contour diagram of the body of the HH 111 jet from an Hα HST image.

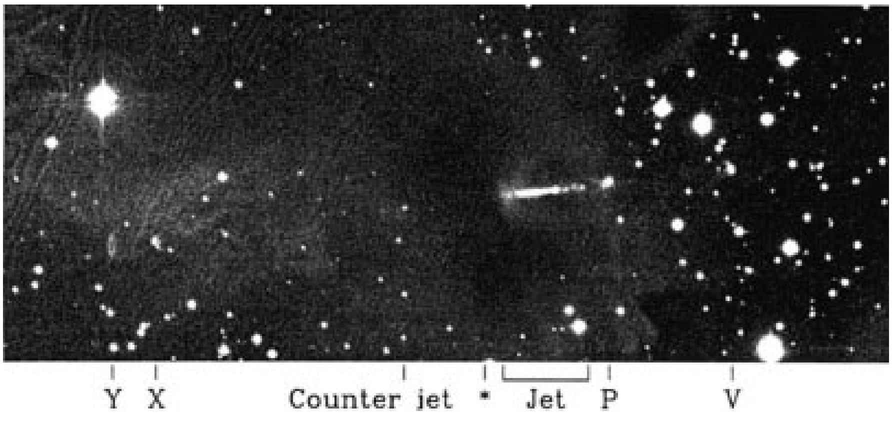

Figure 4: HST image of the HH 111 complex as observed with the 3.6-m telescope with a combination of Hα and [SII] filters.

Figure 6: A multitude of HH flows can be seen in this wide-field image of the young cluster NGC 1333 taken at the 0.9-m telescope at Kitt Peak.

highly obscured and consequently faint. However, in the infrared the jet shows a remarkable symmetry [8]. The entire complex spans a length of 0.8 pc.

The driving source, IRAS 05491+0247, is deeply embedded in the cloud core, with a luminosity of 25 $L_\odot$ and is surrounded by large amounts of cold dust and gas. It is detected in the centimetre radio continuum, and high-resolution VLA maps reveal a small, only 1″ long, radio jet precisely along the axis of the much larger optical jet. Since we know the velocity of the jet, we can deduce that the radio jet is only about one year old, in other words, the star is actively producing the jet at this very moment. The source is presumably a binary, since another jet, only seen at infrared wavelengths, emanates from the source at large angles to the HH 111 axis [8].

The HH 111 complex is associated with a major molecular outflow, consisting of a very large red lobe, where the flow skirts through the southern edge of the L1617 cloud, and a much shorter blue lobe, where the flow escapes from the cloud. Higher-resolution ^{12}CO observations show that the blue lobe is a well-collimated CO jet co-axial with the HH jet [9].

In a detailed spectroscopic analysis of the principal bow shock V, it was found that the ambient medium ahead of the bow shock flows away from the source with a velocity of 300 km/sec [7], which suggests that the bow shock V is not the outermost bow shock, but must have been preceded by even earlier ejecta. This was confirmed when three high-velocity CO bullets were found further out along the jet axis. None of these three bullets are visible optically, but because of their very high space velocities, similar to that of the optical jet, it follows that they are also part of the jet complex.

Figure 5 shows a contour diagram of our Hubble Space Telescope image of the body of the HH 111 jet taken through an Hα filter [10]. The image provides a wealth of new information on the jet structure. The jet appears to be fully resolved perpendicular to the flow direction, and the knotty substructure is rich and complex. The body of the jet terminates in a bright knot, L, which has an

Figure 7: An Hα image of the HH 110/270 flows obtained at the NTT.

obvious bow-shock morphology. In the body of the jet, most of the brighter knots also have bow-shock shapes, with a compression in the contours in the flow direction. Bow shock wings sweep backwards on either one or both sides of the bright knots. At the base of the jet, where it emerges from the dense cloud core surrounding the embedded star, another large bow shock, E, is just about to appear. Apart from these two bright bow shocks, the jet maintains a fairly constant width along its axis, averaging about 0.8″, or 350 AU. The image provides strong support for the notion that knots in HH jets consist of small bow shocks. Since the HH 111 jet is almost perfectly straight, with only a minor wiggling, directional variability is not nearly as important an influence as for the HH 47 jet, and the knots are therefore likely to form as fast jet material overruns slower jet material.

In a recent study, we have searched along the well-defined jet axis for more distant bow shocks, and quite to our surprise we found two large working surfaces each located half a degree on the sky from the source [11]. We have convinced ourselves that they are indeed part of the HH 111 complex, because not only are they lying precisely on the jet axis and are perfectly symmetric around the source, but our proper-motion measurements show that they each move away from the source with highly supersonic velocities. With an angular extent of almost 1 degree, corresponding to 7.7 pc at the distance of Orion, HH 111 is the largest known HH flow in the sky!

5. The Impact of Jets on their Ambient Medium

Following the discovery of giant HH flows at HH 34 and HH 111, we have made a systematic search for other giant HH flows, using the ESO Schmidt telescope in the southern sky, and the Kitt Peak 0.9-m telescope equipped with a large-field CCD for the northern hemisphere. We now have recognised of the order of 20 parsec-scale HH flows, suggesting that such enormous extents are common properties of HH jets. This has important implications for our understanding of the underlying physics of mass-loss phenomena from new-born stars, and their effect on the surrounding interstellar medium. Firstly, since shocks in parsec-scale flows trace ejecta that are progressively older with increasing distance from the source, it may be possible with detailed studies of such gigantic flows, at least in part, to reconstruct the mass-loss history of the driving source. Secondly, when fast shocks propagate through the interstellar medium near or between molecular clouds, they may dissociate molecules and return the medium to its atomic state, which may help to explain the large observed abundances of species like C I and C II found even where there is no UV radiation from massive stars. Thirdly, HH flows may be an important source of momentum and energy injection into their parent clouds, and they may be able to contribute to the turbulence measured in dark clouds. This again may lead to self-regulation of star formation.

A stunning case of how star formation can transform a dark cloud is seen in Figure 6, which shows an Hα+[SII] wide-angle (23 arcmin) CCD image of the NGC 1333 molecular cloud in Perseus [12]. Hα emission is red and [SII] is blue-green. A cluster of about 150 low- to intermediate-mass young stars have been found by infrared surveys in the cloud. Many of these new-born stars are actively forming outflows, and our image shows over 30 groups of HH objects driven by over a dozen young stars. The density of HH flows in this cloud is so high that flow confusion becomes an important issue. Some HH objects are seen well outside the boundary of the opaque cloud, and may be part of giant HH flows, which have burst out of the cloud, and now dump their kinetic energy into the surrounding interstellar medium. The flows show a great variety of morphologies, from amorphous structures to the exceedingly collimated HH 333 jet towards the top of the image, which has a length-to-width ratio of over one hundred!

When flows are ejected from their energy sources, they are not always allowed to coast in a straight trajectory. Molecular clouds are highly complex structures, and if a sufficiently dense cloud core is blocking the way for a jet, rather spectacular fireworks may result. Figure 7 shows an Hα+[SII] mosaic of the HH 110 flow in Orion, obtained at the NTT [13]. This flow was for years puzzling, because despite its rather well-defined structure it was impossible to find an energy source along the flow axis. But when a deep image was taken at the NTT, it became evident that there is a second much fainter flow in the region, called HH 270, to the north-east of HH 110 and with an axis pointing towards the apex of HH 110. A proper-motion study revealed that the HH 270 flow is moving with a speed of 300 km/sec directly towards the beginning of the HH 110 jet. The only possible explanation is that the HH 110 flow is the result of the HH 270 flow suffering a grazing collision with an obstruction. The result of the collision is that the high-velocity gas in the HH 270 flow (only part of which is shocked and therefore rather faint) suffers a strong shock while being deflected, and re-emerges as the bright and complex HH 110 flow. The molecular cloud from which HH 110 is seen to emanate is a natural candidate for this obstruction, and indeed, mm observations at the SEST have revealed a cloud core just north-west of the beginning of the HH 110 flow.

6. Jets and the Birth of Stars

Studies of HH energy sources have shown that, as a class, they are among the youngest stars known, and that they are still surrounded by massive envelopes of cold gas and dust [ref.]. Besides that, little is known about these sources and what triggers their spectacular outflows. One important clue comes from the multiple working surfaces found in many HH flows, which suggests that the sources suffer multiple eruptions.

One class of eruptive variables known among young stars is the group of FUors, so named after the prototype FU Orionis. These stars are believed to be ordinary late-type T Tauri stars which undergo brightenings of 5–6 magnitudes and emerge with F–G supergiant optical spectra, while in the infrared they have late M-type spectra with very deep CO absorption bands. This behaviour has been successfully modelled as events of increased accretion through circumstellar disks at rates significantly larger than for ordinary T Tauri stars [14]. The entire disk heats up and becomes self-luminous, and the light from the disk completely swamps the light from the central T Tauri star. Because disks are low-gravity environments they show supergiant features in their spectra, and because they have a temperature gradient outwards from the star, solar-type spectra will dominate in the visual, whereas infrared observations will probe much cooler parts of the disk and show much later spectral characteristics. In their high states, FUors are luminous objects and their spectra show pronounced P Cygni profiles revealing that they possess massive, very high velocity winds.

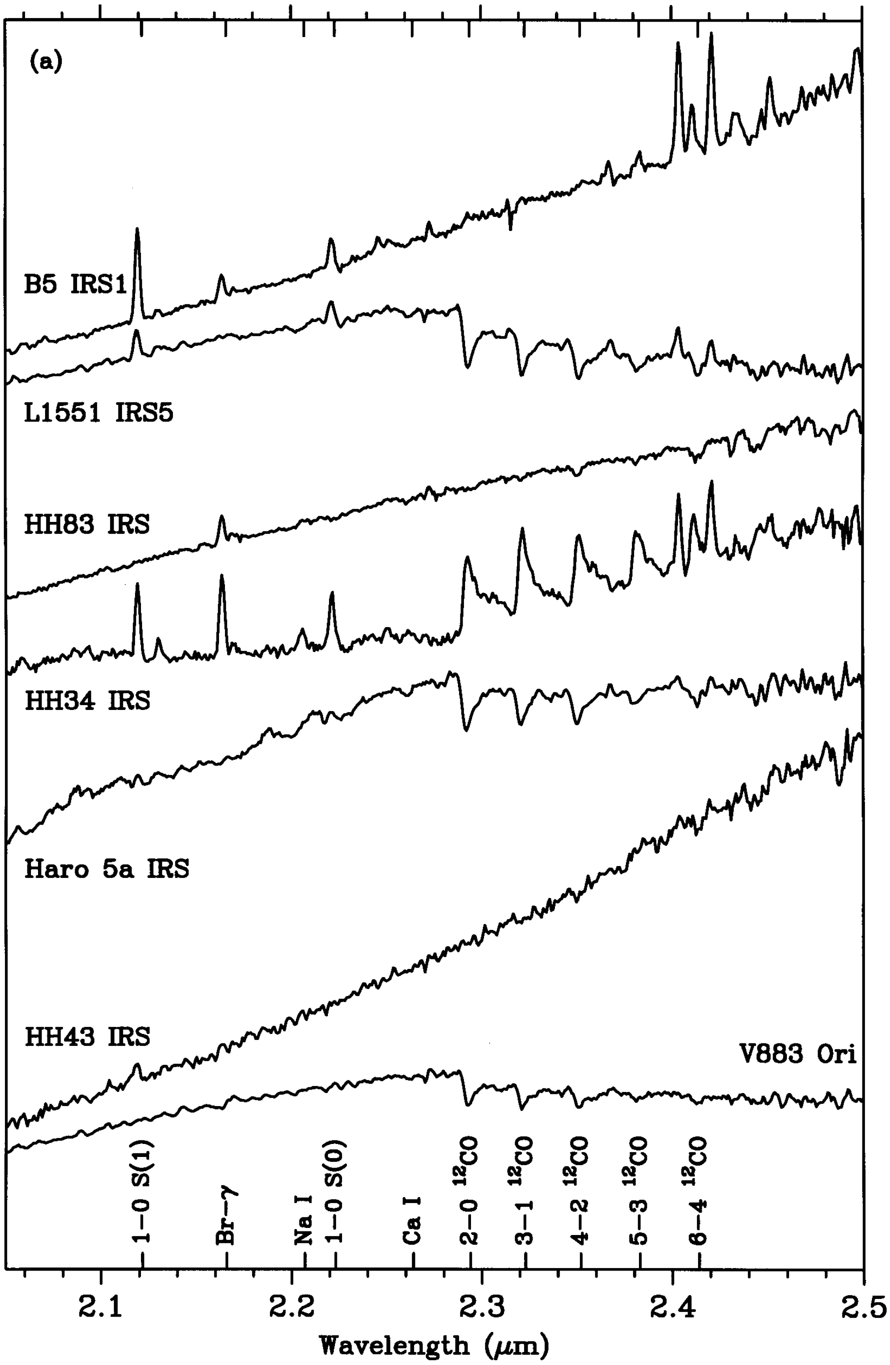

Figure 8: Infrared 2.0–2.5 μm spectra of several HH sources observed with UKIRT.

It has been suggested that FUor events are responsible for the multiple shocks seen in HH flows [15, 6]. Is there any observational evidence to support this contention? Not many FUors are known, and the latest compilation lists only 9 objects. Of these, 3 are associated with HH objects. No other class of young stars have anywhere near such a high percentage of association with HH objects, and yet most HH energy sources are, when they are at all observable in the optical, T Tauri stars. This seems to contradict the idea that FUors should drive HH flows. However, it can be understood when one considers the time scales involved. FUor events are repetitive, and although their frequency of outburst is poorly determined, it appears that they decay to their low, presumably T Tauri, state on timescales of the order of a century or more, but with a large spread for individual objects. The dynamic timescales of the bow shocks in well-defined jets like the HH 34, 47 and 111 jets we have just been discussing, are of the order of 500 years or so. Therefore, whenever we observe an HH energy source, it is more likely to have already decayed into its T Tauri state than to still be in a FUor state.

We have tried to test this hypothesis by observing a sample of embedded HH energy sources, selected so that most of them have rather high luminosities of many dozens to several hundred solar luminosities. If there is a link between HH flows and FUors, we should expect that a much larger fraction of these higher luminosity sources should be caught while they still show FUor characteristics than among the average HH sources. Since a large number of HH sources are optically invisible, the observations should be made in the infrared. We have made 2.0–2.5 μm spectra at UKIRT of 14 HH sources, of which 9 have luminosities higher than the lowest luminosity FUor [16]. Among these 9 sources, 5 show the deep rotationally broadened CO absorption bands characteristic of FUors, while only 1 of the 5 lower luminosity sources shows such bands. It thus appears that the majority of the high luminosity HH sources observed may presently be in elevated FUor states. Figure 8 shows examples of the spectra obtained.

As a star begins to form in the collapse of a dense condensation of gas, a flattened rotating disk soon forms. A vigorous debate is presently taking place among theoreticians about the precise magnetohydrodynamic mechanism that links infall with outflow, but everybody agrees that mass loss is a necessary by-product of the star-formation process, as a star gradually builds up the mass it will have when it eventually reaches the main sequence. HH jets are the visible component of the supersonic mass loss that accompanies the birth of a star, and as such give us indirect information on the very first evolutionary phases of new-born stars.

Acknowledgements

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A Supernova Found by EROS, Followed with the 1.5-m Danish, and Pictured and Characterised at the 3.6-m Telescope

EROS COLLABORATION

Since 1990, EROS (Expérience de Recherche d’Objets Sombres) has been conducting a search for unseen galactic objects via gravitational microlensing. Our system was upgraded in July 1996 with the installation of the 1-metre Marly telescope in the GPO dome instrumented with two wide-field CCD cameras. The greater part of the observing time is devoted to the search for microlensing events by observing the Magellanic Clouds, the Galactic bulge and the Galactic disk. However, during times when these targets are low in the sky, EROS observes fields at high galactic latitudes in order to search for supernovae at medium redshifts and to measure stellar proper motions. We report here our first supernova discovery (IAU Circular No. 6605).

The new EROS camera consists of two CCD mosaics mounted behind a dichroic cube allowing simultaneous observations in red (750 ± 100 nm) and in visible (560 ± 100 nm) passbands. Each mosaic consists of eight 2048×2048 pixel CCDs and covers a 1.4×0.7 deg^2 field.

We search for supernovae by comparing an image of a given field with a reference image of the same field taken at least one month before. Each observation consists of two 5-minute exposures that are combined to form a ten-minute exposure after identification of cosmic rays. A new image is aligned geometrically and photometrically with the reference image, and the image of superior seeing is processed to match the PSF of the other image. The two images are then subtracted and candidate supernovae are identified in the frame thus obtained. The combined ten-minute exposure makes it possible to identify supernovae up to $V = 21.5$. The semi-automatic analysis software allows the identification of candidate supernovae during the day following observations.

During the new moon period in March 1997, we searched for supernovae in 8 deg^2 using reference images taken in February. One supernova (SN 1997bl) was found at $V = 21.5$ in a galaxy of $V = 18.5$ (see Fig.1).

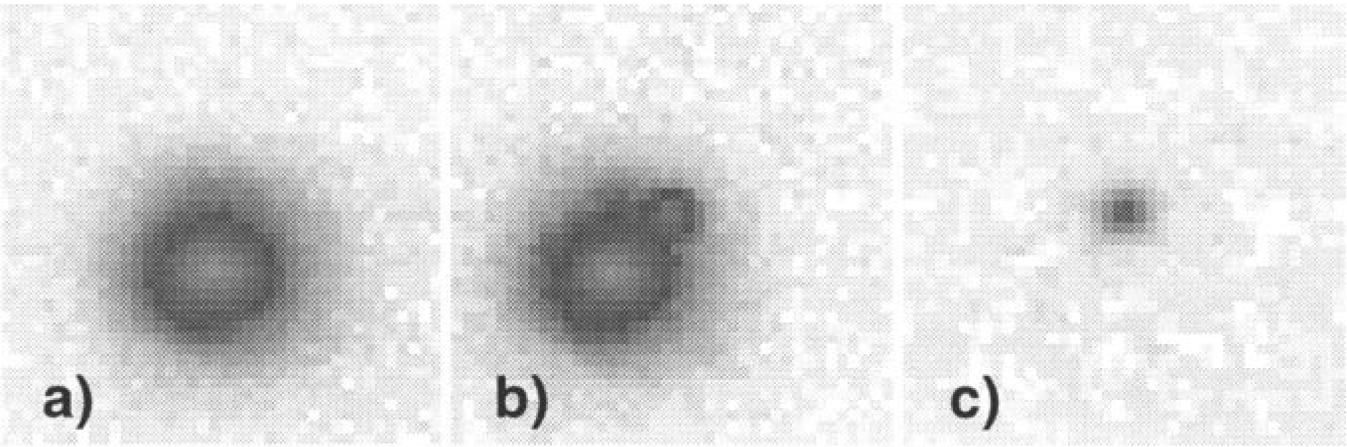

Figure 1: Panel (a) shows the image of the host galaxy, taken on February 3, 1997. Panel (b) shows the image of the host galaxy with the supernova, taken on March 7, 1997. Panel (c) shows the same image as (b) after subtracting the host galaxy image (a). Note that these images are not matched in seeing.