Morphology and Kinematics of Jets from Young Stars

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Abstract

Jets and outflows from young stars accompany the star formation process from its earliest phases until the end of the accretion process. On the observational side, many parameters concerning the morphology, kinematics, and the excitation of the jets have been derived. There is still some debate, however, on their origin and initial collimation mechanism, as well as on the physical processes that cause their characteristic knotty beams. Here, I review what has been acheived so far on the understanding of jets from young stars, and where future work is necessary.

1 Introduction

Jets from young stars are among the most spectacular manifestations of star formation. Usually, the highly collimated beams are accompanied by more extended, less well-collimated molecular outflows. While the jets can be best observed in many forbidden emission lines and atomic resonance lines at optical wavelengths (e. g., Eislöffel 1996, Ray 1996), and as thermal radio jets at cm-wavelengths (e. g., Anglada 1996, Rodríguez 1997), their wider components can be traced in many molecules, such as H_2, CO, and H_2O, from near-infrared through mm-wavelengths (e. g., Bachiller 1996). The jet phenomenon is, however, not restricted to young stars: evidence for highly collimated outflows has also been found in planetary nebulae (e. g., Solf 1993), and some active galaxies, like Cygnus A and M87, are producing extended and powerful jets as well (e. g., Meisenheimer 1996). In fact, in all of these objects the highly collimated outflows seem to be intimately connected to ongoing accretion processes in their central engines. A successful model to explain the relationship between the accretion and the ejection processes by means of rotating magnetospheres has been suggested by Camenzind (1990) (see Fig. 1). Several variations of this model have been proposed since then (e. g., Königl 1991, Ouyed & Pudritz 1993). The principle idea of all these models is that a

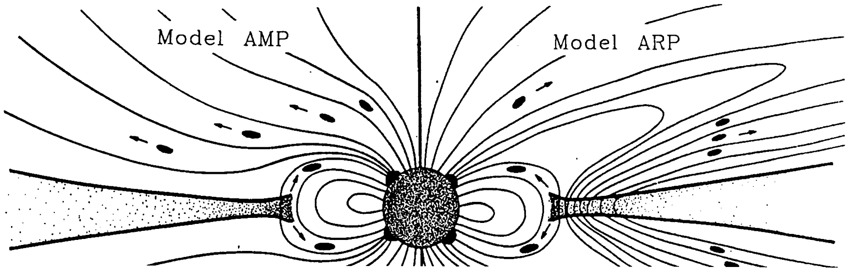

Figure 1: Collimation and acceleration models for the jets from young stars. On the right side, the model of the jet originating from a disk wind as proposed by Camenzind (1990) is sketched, while on the left side the model of a stellar wind origin for the jet as investigated in detail by Fendt, Camenzind & Appl (1995) is shown.

central object is surrounded by an accretion disk, which is threaded by magnetic field lines. Keplerian rotation leads to a winding up of these field lines above and below the disk plane, and to the formation of magnetic surfaces. Charged particles from a stellar wind (Fendt, Camenzind & Appl 1995), an “X-wind” (Shu et al. 1995), or a disk wind (Ferreira & Pelletier 1995) will get trapped in these surfaces and get accelerated and collimated into a beam as they are flung around. Since the central object is accreting matter from the disk that carries a lot of angular momentum, it would get spun up with time, and, in the case of a young star, soon reach its break-up velocity. The jets seem to be a part of the system that is necessary to avoid such disaster, in that they carry away only a small amount of the accreted matter, but essentially all the excess angular momentum. On the other hand, jets and outflows also interact with the surrounding material of the molecular cloud in which their sources were borne, and may have some noticible influence on these clouds: pumping turbulent energy into the clouds, they may be able to support them against further collaps for a while (MacLow et al. 1998), or shred and disrupt them with time. The shock fronts of their bow shocks may compress gas and so trigger further star formation in the vicinity. Jets and molecular outflows are also an excellent laboratory for studying shock physics and chemistry and to learn more about the interstellar medium. Moreover, in some cases the flows act as “navigational lights”, showing us the way to their deeply embedded sources – the youngest known protostellar objects, which otherwise are not detectable at optical or near-infrared wavelengths (e. g., Davis & Eislöffel 1995, Eislöffel et al. 1996, Hodapp 1998, Stanke, McCaughrean & Zinnecker 1998). Thus, jets are not just a beautyful, subordiante matter, but they are a necessary and important ingredient in the star formation process, and therefore well worth being studied in detail.

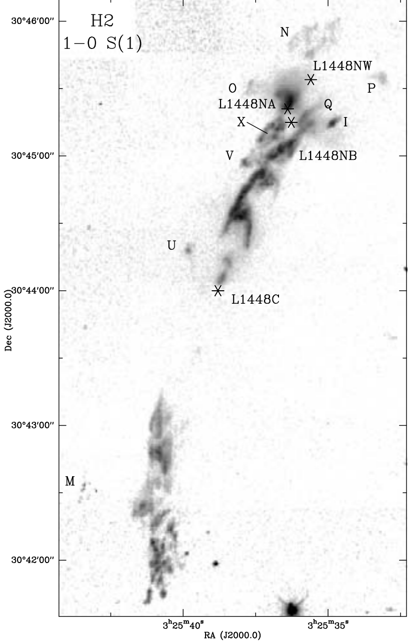

Figure 2: The L1448 outflow region in the 1-0 S(1) line of molecular hydrogen at 2.12 μm. In this region, molecular outflows from four deeply embedded Class 0 sources (L1448 C, NA, NB, NW, marked by "$*$") are seen. Note the extended bow shocks in the northern lobe of the bending flow from L1448C.

2 Evolution of Jets and Molecular Outflows

Protostellar objects seem to start outflow activity as soon as a first protostellar core has formed in a collapsing cloud core (Eislöffel 2000). In these Class 0 objects the sources are very deeply embedded and therefore become visible only in the far-infrared and at (sub-)mm-wavelengths. Although the central objects are invisible in the near-infrared, their flows can be easily detected, for example in the molecular hydrogen lines in the K-band. A prominent example, the flows from four Class 0 sources in the L1448 cloud, is shown in Fig. 2. The observed molecular gas has been found to trace bow shocks of the flows, whose kinematics, excitation, and shock structure are being studied in detail (but will not be discussed here, see, e. g. Davis et al. 1994, Eislöffel et al. 1994, Gredel 1994, Fernandes & Brand 1995, Davis & Smith 1996, Eislöffel et al. 1996, Noriega-Crespo et al. 1996, Ladd & Hodapp 1997, Smith & MacLow 1997, Stone 1997). Although these bow shocks most likely are produced by the highly collimated jets, the jets themselves are not visible in the molecular lines in general. Therefore, their beams cannot be studied directly during the earliest phases of star formation. Only at later times, when much of the molecular core has been accreted or dispersed, and the extinction towards the central source has decreases to a few magnitudes in the optical, do the jets themselves become visible at optical wavelengths. In the following, we will discuss these jets and their properties in more detail.

For how long do jets and outflow activity then go on during the star formation process? Recently, longslit spectroscopic studies of "micro-jets" near T Tauri stars and Herbig Ae/Be stars (Hirth, Mundt & Solf 1994, 1997, Corcoran & Ray 1998) and subsequent direct imaging (Mundt & Eislöffel 1998) have shown that the jets remain active to fairly late stages in the T Tauri evolutionary phase. Apparently, they become fainter and less massive with time, and they disappear when accretion from the disk onto the star ceases, and the disk turns into a passive, protoplanetary disk.

3 Morphology of Jets

The most fascinating feature of the bipolar jets from young stars are their highly collimated beams, that are made up of a series of emission line knots. They were discovered by Mundt & Fried (1982). Usually, at the end of the beams away from the source a bow shock is found, which is considered as the working surface of the jet. These bow shocks often are much brighter and more extended than the jets themselves. They are known since the 1950's as Herbig-Haro (HH) objects (Herbig 1951, Haro 1952, 1953). They show characteristic emission line spectra, very similar to those of the jet knots, with forbidden lines and atomic resonance lines in the optical. Usually, the strongest and most studied lines are those from Hα, [S II] $\lambda\lambda$ 6716, 6731, [O I] $\lambda\lambda$ 6300, 6363, and [N II] $\lambda\lambda$ 6548, 6583. Such spectra are typical for shock-heated gas, and therefore both the jet knots and the HH objects have been identified with cooling gas behind shock fronts (Schwartz 1975).

In the early days it seemed that the jets just fit onto the available CCD detectors, with a field of view of a couple of arcmin. Statistics then yielded values of a few tenths of a parsec for the typical length of jets (Mundt, Brugel & Bührke 1987). Only recently, with the advent of large-format CCDs, wide-field cameras, and mosaicing techniques many examples of jets and HH flows were found that are much larger than previously thought, and reach lengths of over one parsec (Bally & Devine 1994, Eislöffel & Mundt 1997, Reipurth, Bally & Devine 1997). Two such parsec-scale flows are observed in the HH 24 region shown in Fig. 3. Meanwhile, systematic surveys of entire star forming regions are underway, for example with the Tautenburg Schmidt telescope (see Ziener & Eislöffel 1999 for a survey of the Serpens star forming region). They will provide us with a census of outflow activity, and better statistics on the length of outflows. Hence, they will also improve our knowledge of other interesting physical parameters, like outflow age and total energy dumped into a star forming cloud by the active flows in its interior. A first study has shown that at least 25 % of the flows are longer than one parsec (Eislöffel 2000), with a few objects reaching up to 10 pc (Devine et al. 1999). These objects most likely have long broken out of their parental cloud cores, and

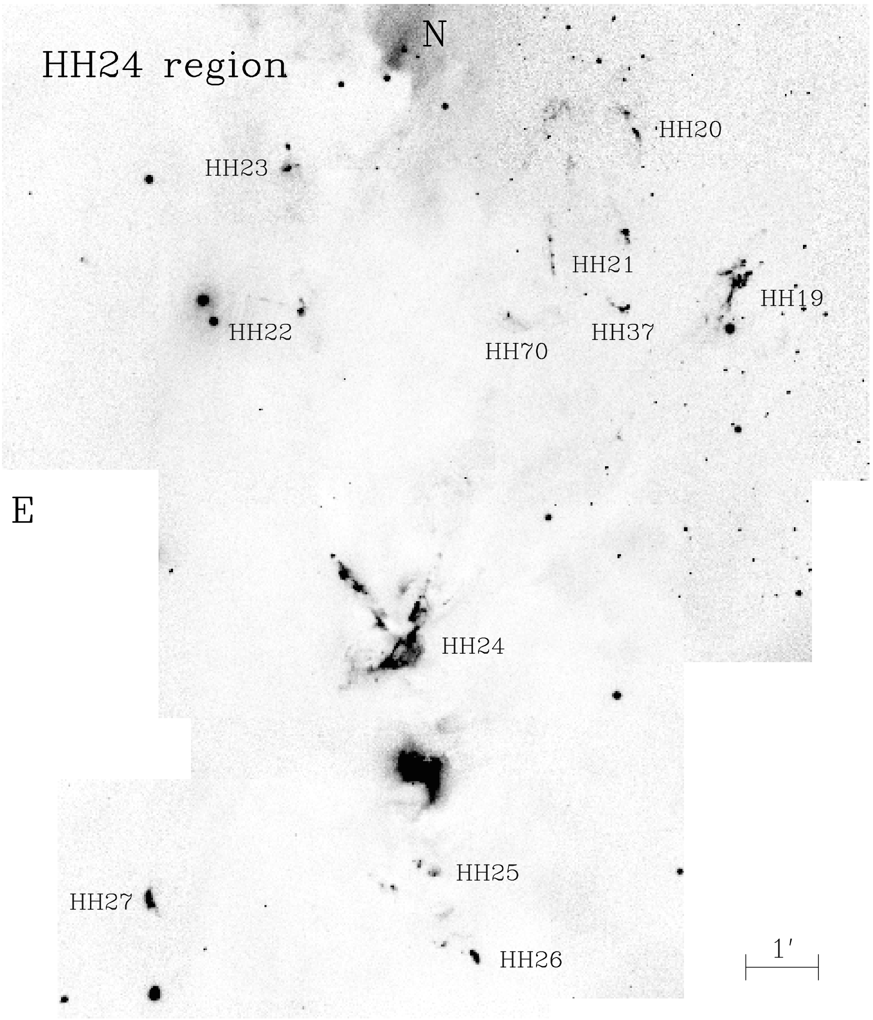

Figure 3: A deep mosaic of the HH 24 region taken at the 3.5-m telescope on Calar Alto in the [S II] λλ 6716,6731 lines. At least eight jets and outflows have been found in this region. At least two of them are of parsec-scale length: the fine jet pointing from HH 24 roughly north to the giant bow shock HH 20/21/37/70, and a second jet with its source in HH 24, which is stretching in southeast–northwest direction between the bow shocks HH 27 and HH 19.

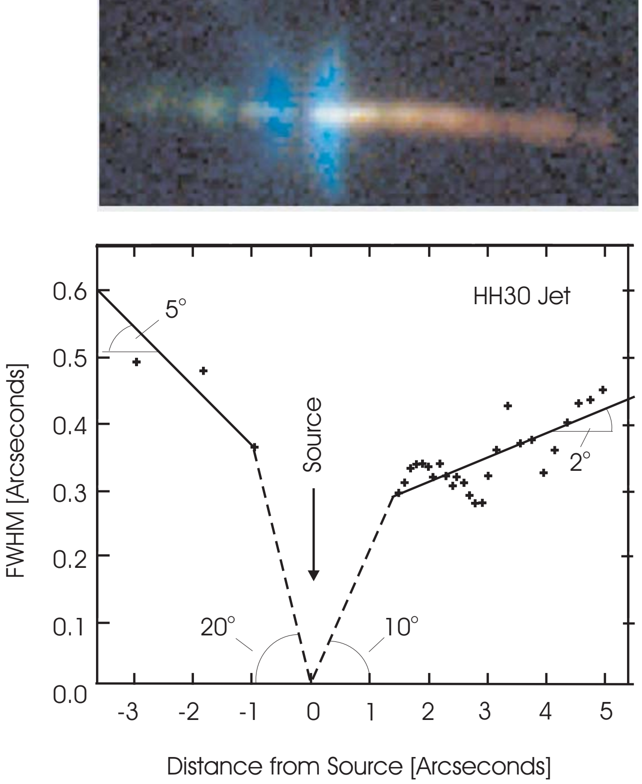

Figure 4: HST image and measurement of the jet diameter in the HH 30 jet. While opening angles of 2° in the jet and of 5° in the counterjet are measured at distances larger than 1.″5 (about 225 AU) from the source, they must be much larger closer to the source (here indicated by dashed lines), if the jet originates from the star or from the inner disk (see also Fig. 1).

probably have reached regions with low density in the interstellar medium, so that they are no longer capable of producing shocks which would heat the gas enough to make it visible. Therefore, their true dimensions may remain unknown.

4 Collimation of Jets

The high degree of collimation that jets maintain over large distances is striking. Some HH flows show length-to-diameter ratios of more than 30 (e. g. Mundt et al. 1990). In order to quantify this property, and to shed some light onto the mechanism responsible for the initial collimation of the beams, the jet diameters as a function of distance from the source have been measured for a number of flows on high-quality ground-based CCD images (Mundt, Ray &

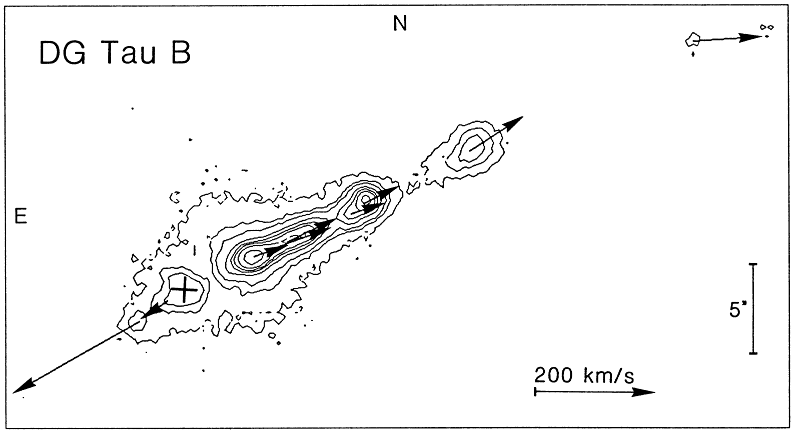

Figure 5: Proper motions in the DG Tau B jet, as measured in the [S II] $\lambda\lambda$ 6716,6731 lines. Tangential velocities of 100 to 300 km s^{-1} are inferred from these measurements, with errors of about ±10 %. The jet source has been marked by a "+".

Raga 1991, Raga, Mundt & Ray 1991, Eislöffel, Mundt & Böhm 1994). Typical opening angles measured along the flow are of 0.5 to 5 degrees. Ground-based observations, on the other hand, cannot reach to the interesting region closer than about 2 arcsec to the source, because of the brightness of the star, an eventual reflection nebula surrounding it, and the seeing. Therefore, the Hubble Space Telescope with its high spatial resolution has been used to measure jet diameters closer than 2 arcsec to the source in several jets (Ray et al. 1996, see also Fig. 4). These measurements seem to show an increase of the opening angle closer to the source, with values of 10 to 20 degrees. Even for the most nearby jet HH 30, however, HST observations did not reach closer than about 150 AU to the source, because of the surrounding reflection nebula. In order to measure opening angles closer to the source and to study the actual collimation region of the jet, one has to resort to indirect measurements (e. g., Eislöffel et al. 2000) or to use future interferometers (Eislöffel & Dougados 1997).

5 Kinematics of Jets

Detailed insight into the kinematics of the outflows can be gained from the proper motions, respectively the tangential velocities, of the knots in the jets and their bow shocks, and from the radial velocities of the gas in the flows.

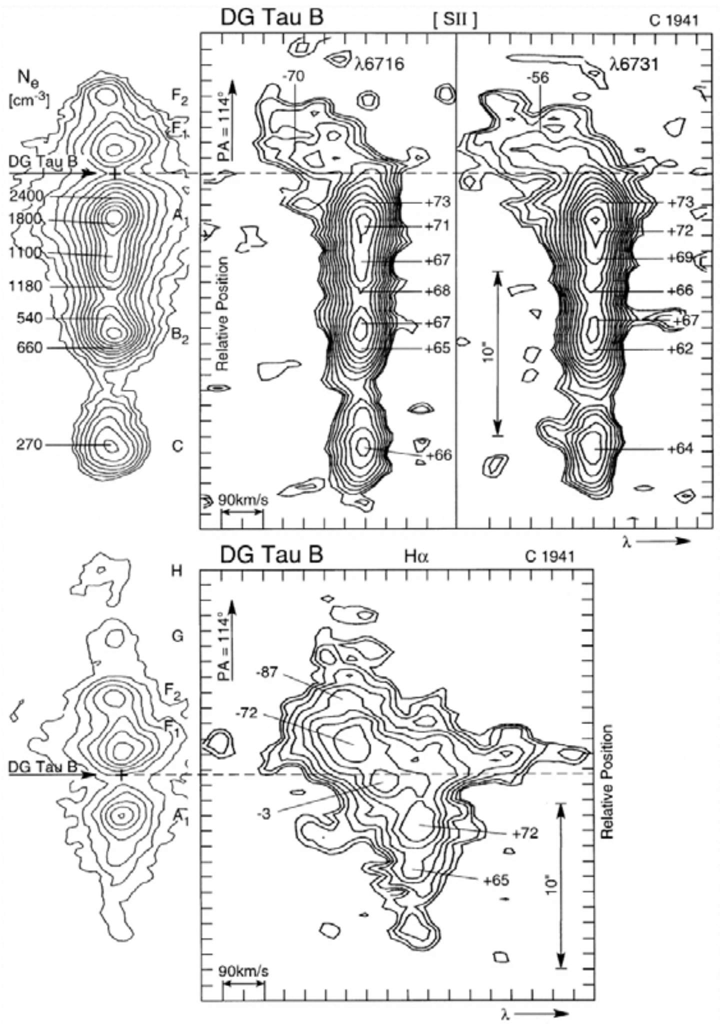

Figure 6: Medium-resolution spectra of the DG Tau B jet taken with the TWIN spectrograph at the 3.5-m telescope on Calar Alto. The top panel shows the [S II] $\lambda\lambda$ 6716,6731 lines, the bottom panel Hα. Radial velocities of the knots are indicated. To the left of the spectra, contour plots of direct images in the respective lines are shown, and the electron densities derived from the spectra are given. The very different brightness ratios between the [S II] lines and Hα in the jet and the counterjet are indicating a much higher excitation in the counterjet.

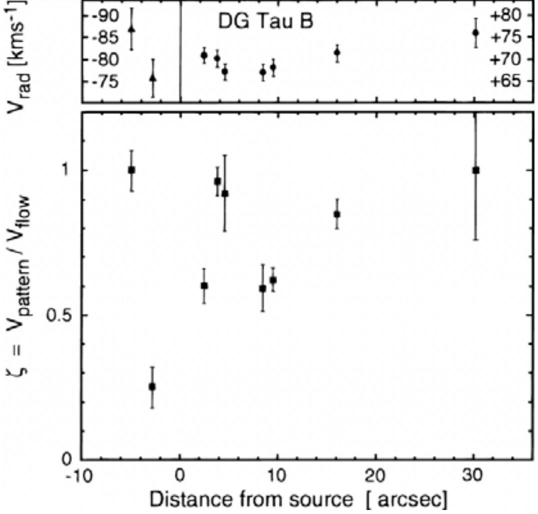

Figure 7: Radial velocities (upper panel) and derived pattern motion of the knots with respect to the outflowing gas in the DG Tau B jet and counterjet (lower panel). Variations by up to a factor of 2 are seen from one knot to the next in some places.

Early proper motion measurements were carried out by Herbig and coworkers on photographic plates (Cudworth & Herbig 1979, Herbig & Jones 1981, 1983, Schwartz, Jones & Sirk 1984). They mostly measured proper motions of HH objects, and that way found several outflows to be bipolar and were able to determine their driving sources. With deeper CCD images taken in the light of the HH emission lines it has become possible to measure proper motions of the individual knots in many jets and their bow shocks to high precision (with errors smaller than 10 % in some cases), and so to get a good sampling of the tangential velocity field. Typically, tangential velocities of the knots of 100 to 400 km s^{-1} are found (e. g., Eislöffel & Mundt 1992, 1994, Heathcote & Reipurth 1992, Eislöffel, Mundt & Böhm 1994, Devine et al. 1997). Such tangential velocities have, for example, been derived for the DG Tau B jet, shown in Fig. 5 (Eislöffel & Mundt 1998). Note that the tangential velocity can vary significantly from one knot to the next. Similarly, radial velocities of 100 to 300 km s^{-1} have been derived for the gas in the flows (Böhm & Solf 1985, Hartigan, Mundt & Stocke 1986, Solf & Böhm 1987, Hartigan, Raymond & Meaburn 1990, Mundt et al. 1990, Reipurth & Heathcote 1991). Longslit spectrograms of the jet and the counterjet of DG Tau B in the [S II] $\lambda\lambda$ 6716, 6731 lines and in Hα are shown in Fig. 6 for illustration (Eislöffel & Mundt 1998). The jets are highly supersonic, and Mach numbers in the flows have been estimated to range from 10 to 40 (Mundt 1986). With the data at hand, one can also estimate the kinematical ages of the flows. Ages of up to 20000 years have been derived for the parsec-scale flows (Eislöffel & Mundt 1997).

From the kinematical data, and with reasonable assumptions, the angle of a flow to the line of sight can be estimated (see Eislöffel & Mundt 1992 for details), and hence true spatial velocities can be derived. That way, it is possible to compare the spatial velocities of the knots and of the outflowing gas directly, and to check for a possible pattern motion of the knots with respect to the gas. It seems that such pattern motions of the knots are indeed rather common: in general, the trains of knots in the beams travel at a lower speed than the gas, and reach equal velocity only in few knots. Moreover, strong variations of the pattern motion are observed in some jets, with $\mathrm{v}_{\mathrm{knot}} / \mathrm{v}_{\mathrm{gas}}$ varying by factors of 2 to 5 between subsequent knots (Eislöffel & Mundt 1992, 1994). Such variations in the DG Tau B jet are illustrated in Fig. 7 (Eislöffel & Mundt 1998).

In the past, our knowledge about the kinematics of jets has strongly influenced the jet models. In a first generation of jet models, the knots were regarded as oblique stationary crossing shock cells, which naturally arise in an initially overpressured jet that moves into a medium with a decreasing density gradient (e. g., Falle & Wilson 1985). This idea was abandoned when the high proper motions of the individual jet knots were measured. In an alternative scenario it was then suggested that the knots may arise from temporal variability of the outflowing gas. Velocity variations of a few percent would lead to the formation of shocks in the form of internal working surfaces in these highly supersonic flows (e. g., Raga & Kofman 1992, Hartigan & Raymond 1993). The knots should then be little bow shocks, which develop where the faster moving gas runs into slower gas ahead of it. Apart from variable outflow velocity also a variable ejection direction, caused, for example, by precession of the outflow source, has been proposed to create bullets in the flow (Raga, Cantó & Biro 1993). All these more recent models have, however, failed so far to explain and reproduce the observed pattern motions of the jet knots with respect to the outflowing gas in a natural way.

6 Variability of Jets

It is conceivable that a flow, ejected at supersonic speed and interacting with its environment, shows some variability. Only few cases of new knots appearing close to a jet source have, however, been reported to date: on a series of CCD images of the L1551 jet Neckel & Staude (1987) found such a new knot that must have been ejected from its source L1551 IRS5 only a couple of years before.

Much longer known is the appearance of new knots in the bow shocks of the HH 1/2 system. There, Herbig (1969) saw three new knots appear on his photographic plates from the 1940's and 1950's. These knots must have undergone brightness changes of several magnitudes. A photometric variability study on CCD images taken in the [S II] $\lambda\lambda$ 6716,6731 lines (see Fig. 8) showed, that virtually all measured knots in the HH 1/2 system were variable by 10 to 30 % within the timespan of only six years (Eislöffel, Mundt

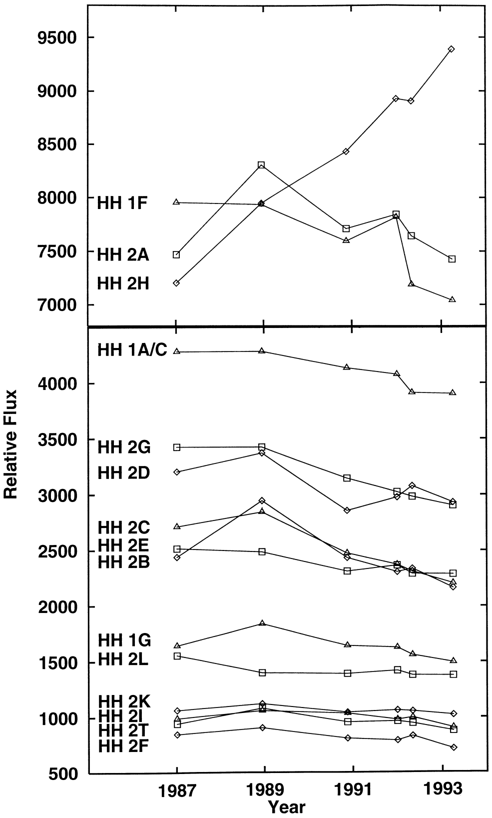

Figure 8: Photometric variability of the knots in the HH 1/2 system, as measured in the [S II] λλ 6716,6731 lines. All knots are found to be variable at a level of 10 % or more over the observed six year period.

& Böhm 1994). One of Herbig's new knots, HH 2H, was still brightening in the early 1990's, and by then had become the brightest knot in the whole system, while the other knots that appeared in the 1950's are fading again.

Although strong photometric variablity has been observed, surprisingly, so far no variability in the shape of jet knots has been reported. Possibly, the fact that many knots are not well resolved in ground-based observations is responsible for this, and repeated observations of jets with the Hubble Space Telescope will also reveal us noticible morphological changes in their knots.

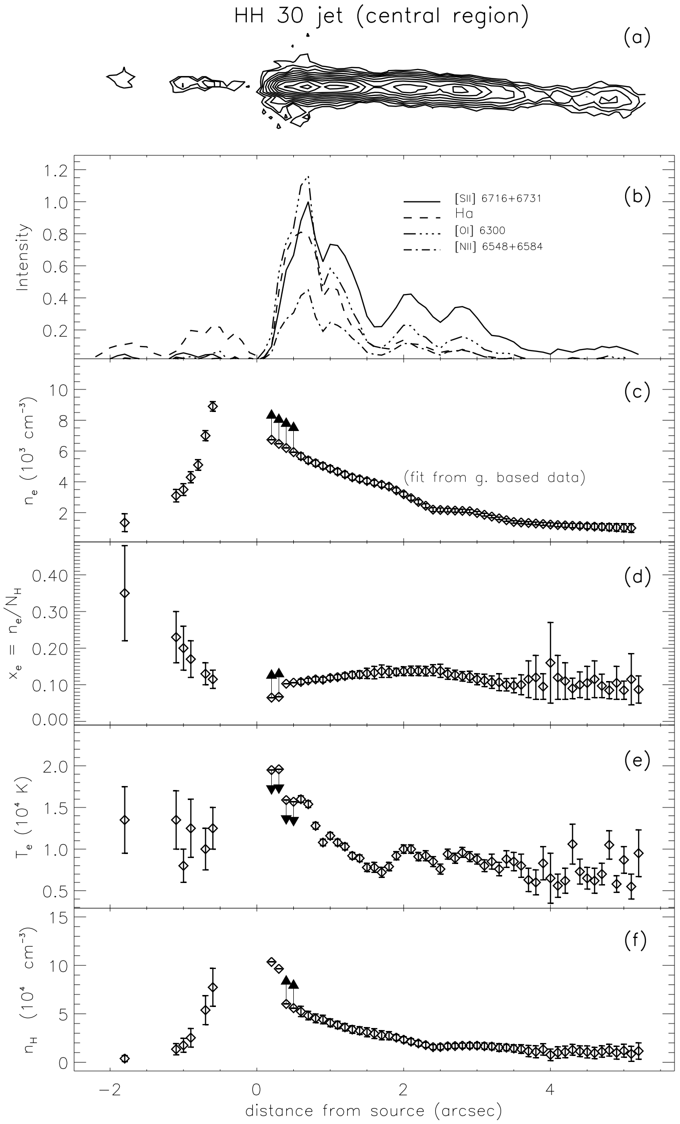

Figure 9: Gas properties along the HH 30 jet. (a) contour plot of a continuum-subtracted HST image in the [S II] $\lambda\lambda$ 6716,6731 lines, (b) intensity tracing in various lines integrated across the jet beam, (c) derived electron density n_e, (d) hydrogen ionisation fraction x_e, (e) average excitation temperature of the forbidden emission line region (f) total hydrogen density $n_H = n_e/x_e$. While the temperature follows the intensity pattern of the knots, both density and ionisation fraction are smooth functions of distance from the source, without any pronounced variations at the position of the knots.

7 Properties of the Gas in the Jet Beams

In the discussion of the kinematics of jet knots it was mentioned already that current jet models of internal working surfaces do not work well in explaining and reproducing observed pattern motions of the knots. Therefore, it seems interesting to study the properties of the gas in the jet beams in more detail in order to see if they are consistent with the notion of the knots as little bow shocks moving in the flow. In particular, one would like to know the electron density n_e, the ionisation fraction x_e, and hence the total gas density n_H, as well as the temperature T of the gas along the beam. A programme is currently underway to determine and analyse these quantities in a number of jets. A first survey at low spatial resolution of several jets has shown that the ionisation fraction of the gas along most beams is of the order of 5 to 40 % (Bacciotti & Eislöffel 1999). So far, in no case could evidence for re-ionisation of the gas in bow shocks along the beam be found. Three jets in the observed sample, HH 24 C, E, and G, are showing re-ionisation events, however, the spatial decrease of the ionisation fraction is not compatible with bow shocks traveling in the flow, but instead with shocks caused by a pinching of the flowing gas.

Obviously, observations at a spatial resolution high enough to well resolve the jet knots are desirable. Such work has started with a detailed study of the HH 30 jet with high spatial resolution narrow-band images from the Hubble Space Telescope, complemented by ground-based longslit spectroscopy (Bacciotti, Eislöffel & Ray 1999). This analysis has shown, that in the HH 30 jet the ionisation fraction rises from 0.065 to 0.140 over the first $2''$ ($\sim$300 AU) of the flow, and then levels out and falls off again to 0.04 at $12.''5$ from the source (see also Fig. 9). Although the knots are well resolved, only a rise in gas temperature is observed across them. No evidence for enhancements of the ionisation fraction or the gas density is seen in the same places. Thus, the knots seem to resemble more plasma instabilities than traveling strong shock fronts. Clearly, to understand the basic physics of jet beams, more observations at high spatial and spectral resolution are necessary, together with further improvements of the jet models.

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