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GENERATING YSO JETS: WHAT THE *HST* HAS TO TELL US

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RESUMEN

Ahora se sabe que los flujos de las estrellas jóvenes son una parte esencial del proceso de formación estelar y hasta pudieran ser necesarios para que ocurra el acreción a través del disco. Mientras que los flujos mismos pueden extenderse algunos parsecs, son, sin embargo, generados dentro de un radio de a lo más unos pocos unidades astronómicas de su fuente. Tales distancias corresponden a escalas angulares de alrededor de unas pocas décimas de milisegundos de arco para las regiones de formación estelar más cercanas. Por lo tanto, hasta que la interferometría óptica/infrarroja cercana se vuelva más disponible, nuestra mejor oportunidad de explorar la formación de chorros de estrellas jóvenes está en el *Telescopio Espacial Hubble* (*HST*). Datos del *HST*, en particular los datos obtenidos con el espectrógrafo de imágenes del telescopio espacial (STIS), ya nos están proporcionando pistas importantes acerca de la formación de estos chorros y estamos empezando a hacer comparaciones directas con las predicciones de los modelos. En este trabajo hacemos una reseña de los avances recientes en el campo. Actualmente, no sólo es posible medir el diámetro y la velocidad del chorro cerca de la fuente, sino que pueden medirse cantidades importantes como son la temperatura y la fracción de ionización, además de las densidades electrónica y total, tanto a lo largo como a través del flujo. Los valores medidos parecen estar de acuerdo con los modelos magnetocentrífugos populares. Finalmente, discutimos el descubrimiento reciente de la posible rotación de los chorros. De gran importancia es el resultado que la cantidad de rotación observada sugiere que los flujos son los responsables de remover el momento angular de los discos y por eso facilitan la acreción.

ABSTRACT

It is now realised that outflows from young stars are an essential part of the star-formation process and may even be necessary for disk accretion to occur. While the flows themselves can stretch for several parsecs, they are nevertheless generated within a radius of at most a few AU from their source. Such distances correspond, for the nearest star-forming regions, to angular scales of around a few tens of milliarcseconds. Therefore, until optical/near-infrared interferometry becomes widely available, our best chance of exploring how jets from young stars are produced lies with the *Hubble Space Telescope* (*HST*). Already *HST* data, and in particular data obtained with the Space Telescope Imaging Spectrograph (STIS), are giving us vital clues regarding their formation and we are beginning to make direct comparison with model predictions. Here we review recent advances in the field. Not only is it now possible to measure jet diameter and velocity close to the source but also important quantities like temperature, ionization fraction, as well as electron and total density, both along and across the flow. The values obtained appear to be in agreement with popular magneto-centrifugal jet launching models. Finally, the recent discovery of possible jet rotation is discussed. Of major importance is the finding that the amount of rotation observed suggests outflows are responsible for removing angular momentum from disks, thereby allowing accretion to occur.

Key Words: **ISM: JETS AND OUTFLOWS — STARS: MASS LOSS — STARS: PRE-MAIN SEQUENCE**

1. IN THE BEGINNING

Perhaps the two major advances in star-formation studies in the past couple of decades, at least from an observational perspective, are the discoveries of outflows and disks around young stars. The two phenomena, as we know, are intimately related: for example the mass-loss rate through an outflow seems to be function of the mass accretion rate (Hartigan, Edwards, & Ghandour 1995). An extreme case that illustrates this point is that of the weak-line T Tauri stars, pre-main-sequence stars that otherwise resemble classical T Tauri stars, with the major difference that they do not possess an active accretion disk. No extended outflows are seen from weak-line T Tauri stars.

Outflows themselves can be observed over a wide range of wavelengths from the radio to the X-ray bands (Eislöffel et al. 2000; Pravdo et al. 2001). Depending on the band, the radiation may take the form of line emission or a broad continuum. Moreover, the morphological appearance of an outflow and its kinematical details depend strongly on the wavelength chosen, even within the same band. For example, in low-excitation transitions of the CO molecule an outflow may appear to be moving rela-

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tively slowly (≈ 10 to $30\,\mathrm{km\,s^{-1}}$) and to look poorly collimated, while in higher excitation lines, the same outflow is observed to be moving quickly (≈ 80 to $120\,\mathrm{km\,s^{-1}}$) and to be very well collimated.

The general consensus at present is that all outflows from young stars, including the poorly collimated molecular flows mentioned above, are ultimately powered by highly focused jets. That said, there are alternatives to this "mainstream" scenario (see Lee et al. 2001 for a discussion of this point). The jets themselves may not always be optically visible, particularly, for example, those associated with the so-called Class 0 and I sources. Such young stars are often highly embedded and the optical extinction, even far away from the source, may be too high to permit us to see the jets directly. If, however, we look in the near infrared and, in particular, we employ a H_2 2.12 μm filter, traces of the jet, or even whole jets, may become visible (Stanke, McCaughrean, & Zinnecker 2000).

Both in the optical and in the near infrared, we see that outflows from young stars can stretch for several parsecs (Eislöffel & Mundt 1997). In any event, the observed lengths of optical outflows (and corresponding dynamical times) appear in most cases to be lower limits dictated more by the characteristic sizes of clumps in molecular clouds than by actual outflow lifetimes. Thus, in reality, many flows have "blown out" of their parent cloud. Moreover, although we see what most observers would describe as a jet close to the source, at larger distances, i.e., on parsec scales, structures tend to be more irregular. This is in line with the idea that most of the knots and features we observe in outflows from young stars are due to "internal working surfaces" caused by velocity variations in the flow. According to this scenario, high-frequency, small-amplitude variations tend to die out with time, whereas slower variations of greater amplitude propagate furthest from the source. Thus, in a classical optical outflow like the Herbig-Haro (HH) 34 system, large-scale bowshocks like HH 34S or HH 34N are due to major eruptions in the past (Raga et al. 2002).

How, however, are these jets generated? This is perhaps one of the major outstanding questions in star-formation studies. It is reasonable to say that through a combination of observation, computer, and laboratory simulation, we know more about how they propagate through their parent cloud than we do about how they are produced. The level of detail seen, for example, in *HST* images and in multi-epoch *HST* movies is now so good (see Hartigan 2003), one might be excused for thinking we can now observe the weather caused by the interaction of the jet with its environment. To date most simulations, with a few notable exceptions (see, for example, Frank et al. 2003) either ignore the region where the jet is produced and concentrate on how jets propagate, or they consider only the zone close to the star and disk. Simulations encompassing both the generation and propagation zones, for want of better terms, are difficult to produce as they cover such an enormous range in scale. This problem, however, will be overcome with the availability of magnetohydrodynamic (MHD) codes with adaptive grids.

What do the observations tell us? First of all one has to consider what type of star is best to observe if we are to peer into the "central engine". Clearly, as the highest resolutions are obtained using optical/near-infrared techniques, Class II outflow sources, i.e., classical T Tauri stars or their higher mass counterparts, the Herbig Ae/Be stars, are ideal. These stars suffer a minimum of extinction in the direction of the generator so one might have some opportunity of seeing it in action. Of course a bright, optically visible source has its drawbacks. In particular, when we are observing an outflow in the optical or near infrared we are looking at relatively faint line emission. Seeing the latter, especially in contrast with a bright central star, can be very difficult. One thus wants to optimise the signal-to-noise ratio of the line emission to the underlying continuum. Clearly, spectroscopy is ideal but one has to be careful not to overdo it with too high a spectral resolution—we are dealing with faint emission lines that, at least close to the source, are comparable in width to their Doppler shifts i.e., of order a few hundred $\mathrm{km\,s^{-1}}$. Thus, intermediate resolution spectroscopy is ideal.

Early spectroscopic observations of T Tauri stars often revealed the existence of two or more velocity components (Hartigan et al. 1995). The so-called low-velocity component (or LVC) with velocities in the range 10 to $50\,\mathrm{km\,s^{-1}}$, along with a high-velocity component (or HVC) with radial velocities as high as a few hundred $\mathrm{km\,s^{-1}}$. It was quickly realised that these two components are physically distinct, that is, they have different levels of electron density, excitation, degree of collimation, etc. (Hirth, Mundt, & Solf 1997). Moreover, long-slit spectroscopy, with the slit orientated in the direction of the outflow from the classical T Tauri star, where known, showed that any extended jet had a velocity close to the HVC and therefore the HVC was likely to be nothing more than the jet on subarcsecond scales. This view was later confirmed by *HST* STIS observations (Bacciotti et al. 2000). According to Kwan & Tademaru (1995) the LVC is probably a low-velocity disk wind that encompasses the jet.

The availability of high spatial resolution both from the ground and from space is starting to revolutionise our understanding of how jets are produced and is beginning to provide direct comparison with theory. For example Dougados et al. (2000) have successfully imaged a number of jets from classical T Tauri stars using adaptive optics (AO) with 0″.2 resolution. Moreover, using spectro-astrometry, Takami et al. (2001) and Davis et al. (2001) have shown how one can extract some information on tens of milliarcseconds scales regarding the spatial distribution of emission in various lines both in the optical and the near infrared. The biggest advances, however, have been due to *HST* and we will examine these in more depth for the remainder of this review.

2. WHAT DID THE *HST* EVER DO FOR US?

Early *HST* studies concentrated on imaging jets rather than kinematical studies, primarily because of the lack of appropriate on-board spectroscopic instrumentation. Previously unresolved knots in the flow, particularly those close to the source were seen, with higher resolution, to often look like planar or slightly bow-shaped shocks perpendicular to the outflow direction (Ray et al. 1996). Their appearance, in fact, was consistent with the idea that they were "internal working surfaces" within the jet due to velocity variations in the flow (Raga et al. 2002)

The availability of high-resolution images means that one can determine jet diameters. As the jet widths are only at best a few tenths of an arcsecond close to the source, a measure of the jet diameter is normally provided by the FWHM of a Gaussian fit. This approach, however, is problematic as we have to understand what, precisely, we are measuring. According to some jet generation models, notably the X-wind model (Shu et al. 2000), the jet is in effect just the brightest, most excited, portion of the flow and it is surrounded by a much broader cooler outflow. If this is the case then Gaussian fitting will only give us a lower limit for the true jet diameter. Alternatively, if the knots we are observing close to the source are true bowshocks then what we measure is the diameter of the bow and not the true jet width. With these provisos understood, studies to date have shown that a relatively high degree of collimation is already achieved very close to the source, i.e., within 10 to 20 AU, in agreement with MHD launching models. Measured diameters in different emission lines are relatively similar for the same jet

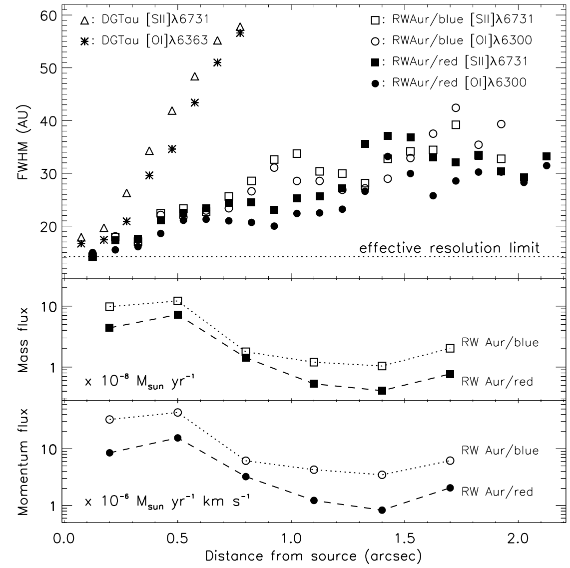

Fig. 1. Plot of the variation in diameter (FWHM), for the initial sections of the blue- and red-shifted jets from RW Aur and the blue-shifted jet from DG Tau versus distance from the source (Woitas et al. 2002). $\dot{M}_{\rm jet}$ and $\dot{P}_{\rm jet}$ are also plotted for both RW Aur jets.

although variations in jet opening angles are seen (see Figure 1).

The availability of STIS on board *HST* has meant that one can also, using line diagnostic techniques, determine such parameters as electron density, temperature and ionization fraction both along and (where resolved) in the direction transverse to the jet flow. Coupled with velocity information one can then obtain such fundamental quantities as jet momentum- and mass-loss rates.

Electron densities, for example, are found to be typically of order 10^2 to $10^3\,{\rm cm}^{-3}$ in jets at distances of several hundred AU from the source. Closer in, however, the densities rise, as one might expect, to 10^4 to $10^5\,{\rm cm}^{-3}$ and beyond. The important parameter to determine, however, is the hydrogen ionization fraction $x_{\rm e} = n_{\rm e}/n_{\rm H}$ so that one has a true measure of the jet density. Two very different methods are available to do this (see Hartigan, Morse, & Raymond 1994 and Bacciotti & Eislöffel 1999), although we will not go into their details here. It suffices to say, however, that, to a first approximation at least, both approaches yield similar values of $x_{\rm e}$, thus we can have some confidence in the jet mass-loss rates, etc., that are derived. Values for $x_{\rm e}$ are in the range 0.02 to 0.5, although it must be said that the lower values are more common. In turn this means that young stellar object (YSO) jets are primarily neutral atomic beams. In fact, the highest jet ionization fractions appear to be reached close to the source (Lavalley-Fouquet, Cabrit, & Dougados 2000; Bacciotti 2002): $x_{\rm e}$ initially rises rapidly with distance, reaches a plateau and initially slowly declines. The cause of the rapid rise in ionization is unknown but Garcia et al. (2001) and Shang et al. (2002) have suggested ambipolar diffusion in disk winds and X-ray ionization in X-winds, respectively.

Combining the hydrogen density with the jet velocity and radius, one can derive the mass-loss rate $\dot{M}_{\rm jet}$ and, using an independent measure of the accretion rate through the disk, such as the degree of line veiling (Hartigan et al. 1995), the very important ratio $\dot{M}_{\rm jet}/\dot{M}_{\rm acc}$ can be found. Derived values for $\dot{M}_{\rm jet}$ differ by several orders of magnitude, from as little as 10^{-9} to $10^{-5}\,M_{\odot}\,{\rm yr}^{-1}$ depending, as one might imagine, on the mass and evolutionary status of the star. If one divides these values by their corresponding disk accretion rates, the ratio $\dot{M}_{\rm jet}/\dot{M}_{\rm acc}$ is found to be typically in the range 0.01 to 0.1. Interestingly, such values are in line with centrifugal MHD models (Königl & Pudritz 2000).

It would be inappropriate to close this section without saying something about asymmetry in bipolar jets. It is normally assumed that all HH flows are bipolar, although clearly statistically we are much more likely to observe the blue-shifted as opposed to the red-shifted jet since the latter normally points back into the parent cloud. That said, a number of jets are seen in the optical/near infrared to be bipolar. What is particularly fascinating about these is that the two jets flowing from the one source may be very different indeed. These differences cannot be explained as extinction effects. For example, they may differ in velocity, excitation, opening angle and so on. Although such asymmetries were previously known on arcsecond scales, recent STIS observations of the bipolar jet from RW Aur (Woitas et al. 2002) show that these differences can be traced right back to within $0\farcs2$ from the source or about 30 AU at the distance of the Taurus Auriga Cloud. There is no reason to expect that such asymmetries do not persist on even smaller scales. Such observations suggest that asymmetries in bipolar jets are due to intrinsic differences in the jets themselves when launched rather than, for example, varying amounts of mass loading on one side of the flow compared to the other.

3. THE HOLY GRAIL: LOOKING FOR JET ROTATION

According to both X-wind and disk wind jet launching models, jet material is ejected centrifugally along magnetic field lines in an analogous way to "beads on a wire". Consider material that is initially launched from the disk at some distance from the star. As the initially poloidal field lines open away from the rotation axis and the material moves outwards, it will obviously acquire a higher and higher toroidal velocity. Clearly, this process cannot continue indefinitely and instead, in the vicinity of the Alfvén surface, the field lines become increasingly toroidal due to the inertia of the material. Two important effects occur as a result. First, the asymptotic toroidal velocity of ejected material is much higher than it was at the material's foot point in the disk. Second, the increasingly toroidal fields focus what initially may have been a broad disk flow into a jet and, from the Alfvén surface onwards, angular momentum is conserved. In this way angular momentum is channeled away from the disk through the jet and, in turn, this allows disk accretion to occur.

Although the models are elegant in their beauty and simplicity, one cannot escape the fact that, to date, there has been very little solid observational evidence to support the idea of centrifugally launched MHD jets, never mind distinguishing between the various flavors available in the literature. Moreover, although the general consensus is that magnetic fields must play an important role in jet production, evidence for dynamically important magnetic fields in outflows from young stars is unfortunately sadly lacking. For example, Ray et al. (1997), using radio interferometry, found quite strong magnetic fields in the outflow from T Tauri South at distances of a few tens of AU. As T Tauri South, however, may have undergone an EX Orionis-type outburst a few years before, it is not clear how typical such fields are.

Obviously, one prediction of MHD centrifugally launched jet models is that the jet asymptotically has, on average, a higher angular momentum per unit mass than its parent disk. Thus, it would be extremely useful to see whether jets rotate and to determine not just $\dot{M}_{\rm jet}$ but $\dot{J}_{\rm jet}$ as well. The first possible evidence for rotation in a jet, HH 212, was made by Davis et al. (2000) using near-infrared long-slit spectroscopy. Shifts of a few ${\rm km\,s^{-1}}$ were discovered transverse to the flow in a series of knots. These shifts were superimposed on the general outflow velocity and were only seen at large distances from the source (several thousand AU) where the flow conceivably has interacted, and may have been buffeted, by its environment. That said, the apparent sense of rotation matches that of the ammonia core surrounding the source of HH 212 (Wiseman et al. 2001).

Recently we (Bacciotti et al. 2002) have searched for evidence of rotation in jets much closer (i.e., within 100 AU) to the source using STIS. This study is part of an ongoing *HST* investigation. The first clue that rotation may be seen in existing data came from an analysis of seven slit spectra of the blue-shifted DG Tau jet. The slits were positioned along the flow but at varying offsets from the central axis so as to build up a 3-D intensity-velocity "cube". In this way we were able not only to measure radial velocities along the flow but also to see variations in radial velocity in the transverse direction. Careful measurements showed, using both Gaussian line fitting and cross-correlation techniques, systematic differences in velocity from one side of the jet to the other. The differences observed ranged from 6 to 20 km s^{-1}. If we then take into account the angle of inclination of the flow with respect to the line of sight, we can infer typical toroidal velocities of around 5 to 15 km s^{-1} at distances of 20 to 30 AU from the flow axis and at around 100 AU from the plane of the disk (see Figure 2).

It has to be emphasised that the above velocity differences were measured using low- to intermediate-velocity line emission (i.e., $\sim$ 20 to 100 km s^{-1}). This is because the jet is only resolved spatially in the transverse direction for this range. At the same time, the DG Tau jet contains a high-velocity core that is spatially unresolved, even with *HST*, in the transverse direction to the outflow. Obviously, no measurements of toroidal velocities could be made for the core. Despite this fact, calculations show (Bacciotti et al. 2002) that a large fraction of the angular momentum transport necessary for the disk to accrete at the rate it does occurs through the low- to intermediate-velocity outflow. Finally, we add that ^{13}CO(2–1) line observations (Testi et al. 2002) of the DG Tau disk show it to be rotating in the same sense as the observed outflow from DG Tau. As in the case of HH 212, the chance of the sense of rotation being the same is fifty-fifty but collectively the case is strengthening!

4. CONCLUSIONS

High spatial resolution observations, especially those undertaken with the *HST*, of jets from young stars have proven to be very fruitful. This is particularly so in the vicinity of the source. Observing, however, optically visible sources with outflows has it drawbacks and, in particular, it is difficult to image the line emission from the jet in contrast to the bright stellar continuum. The optimum solution then is to use intermediate dispersion spectroscopy as has been done for a number of jets.

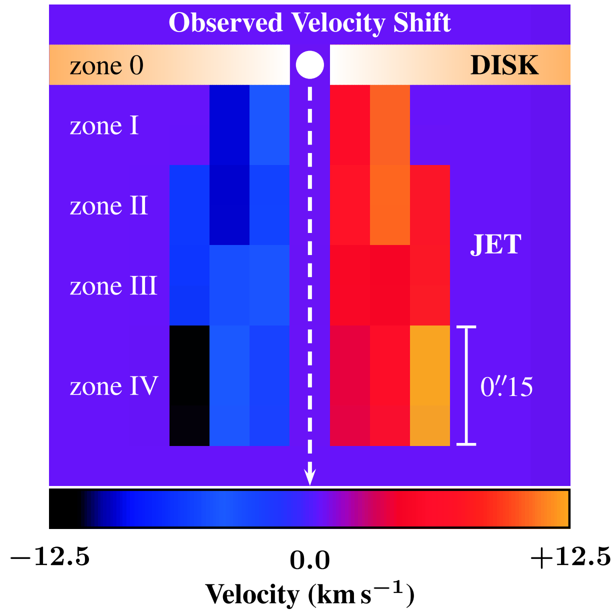

Fig. 2. Possible rotation in the DG Tauri outflow. Schematic map of the systematic velocity shifts at the base of the jet derived (at low velocity) from STIS observations (Bacciotti et al. 2002). NOTE: THIS FIGURE IS AVAILABLE IN COLOR IN THE ELECTRONIC VERSION OF THIS ARTICLE, OBTAINABLE FROM `http://www.astroscu.unam.mx/~rmaa/`.

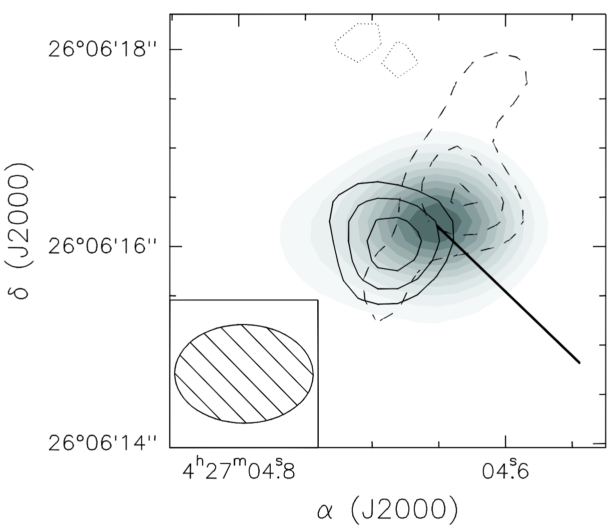

Fig. 3. Rotation in the DG Tau disk, observed as blue and red wings in the ^{13}CO(2–1) line (solid and dashed contours, respectively). The grey area shows the 1.3 mm dust continuum, and the solid line indicates the direction of the DG Tau. Note that the rotation is in the same sense as that of the jet. (From Testi et al. 2002.)

Some very interesting findings are emerging from *HST* observations of the optically visible Class II outflow sources:

- One can measure such quantities as temperature, hydrogen density, ionization fraction and velocity close to the source not only along the outflow but in the transverse direction as well. These data are already providing important clues for modeling purposes.

• In at least two outflows, evidence has been found for rotation and in both systems it is in the same sense as that of the associated disk/envelope. In the case of DG Tau we see that the low- and intermediate-velocity outflow transports a significant fraction of the total angular momentum that needs to be lost by its disk for it to accrete at the rate it does.

• The ratio of mass loss through the flow to mass accretion through the disk is roughly in line with what is expected from magneto-centrifugal jet launching models.

Although the evidence to date is in line with existing MHD models, higher resolution is required to confirm this picture. Moreover, the spatial resolution available with the *HST* is just on the limit of what is useful for probing the central engine; tens of milliarcsecond resolution are needed if we are to discrimate between the various MHD models. The prospects, however, are bright in this regard as the next generation of interferometers, such as AMBER on the VLT, come online. With these instruments we will be able to resolve the jet acceleration region in unprecedented detail. Despite the centrifugal MHD jet model being initially proposed in the context of giant extragalactic radio jets, it would be ironic if validation of the model came first from observations of their more humble Galactic cousins.

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