Mem. S.A.It. Suppl. Vol. 5, 113

Memorie della
Supplementi

HST reveals the origin of Stellar Jets: first validation of the magneto-centrifugal acceleration

Francesca Bacciotti

INAF-Osservatorio Astrofisico di Arcetri, L.go E. Fermi 5, 50125 Firenze, Italy; e-mail: fran@arcetri.astro.it

Abstract. The spectacular collimated jets observed in association with young stars stand as a fundamental ingredient of the star formation process. For example, they allow the matter to accrete through the disk onto the star, since in principle they can extract all the excess angular momentum from the system. To explain the origin of jets, a mechanism of magneto-centrifugal acceleration has often been invoked, but its observational confirmation has been very scarce in the past, due to the small scales involved. Very recently, however, observations made by our group with the spectrograph STIS on board the Hubble Space Telescope (HST) have finally provided a mean to test the paradigm of magneto-centrifugal acceleration. Thanks to HST high angular resolution (0.”1) our analyses of outflows from evolved T Tauri stars (TTSs) have allowed us to determine for the first time the actual morphology of the jet and its excitation and kinematic properties of in the initial 100 AU, i.e. in the acceleration and collimation region contiguous to the disk. In particular, the recent detection of *rotation of the flow* around its symmetry axis has finally confirmed the validity of the magnetic approach, and a number of properties have been derived that appear to favour disk-wind models, although X-winds can also play a role in the innermost part of the flow.

Key words. ISM: jets and outflows – Stars: Formation, Pre-Main Sequence – High angular resolution

1. Introduction

Supersonic collimated jets powered by young stellar objects (YSOs) are believed to be a key element of the star formation process (Reipurth & Bally 2001). According to popular theoretical scenarios, magnetic and centrifugal forces act together to launch the jets along magnetic field surfaces, either from the star vicinity ($\leq$ 0.1 AU for the *X-wind*, Shu et al. (2000)), or from the inner circumstellar disk (a few AUs from the star for the *disk-wind*, see, e.g. Königl & Pudritz (2000), Ferreira (2002)). The main attractive of this kind of models is that the magnetic field along which the matter is launched also brakes the rotation of the disk. In this way some angular momentum is extracted from the system, so that the matter in the disk can flow inward and finally accrete onto the central star. All the models proposed within this class predict that the jet properties are defined within the initial 100 AUs from the source. Despite many sources of ‘classical’ jets being heavily

Send offprint requests to: F. Bacciotti
Correspondence to: INAF-Osservatorio di Arcetri, L.go E. Fermi 5, 50125 Firenze

embedded, the less powerful flows from more evolved TTSs provide us with a ‘window’ on the central engine, as they can be traced back to their origin in optical and near-infrared (NIR) forbidden and permitted lines. Up to four years ago, however, the region of interest was not accessible to direct observation, because sub-arcesecond resolution is needed (the distance of the closest star formation regions is 120 - 140 pc). Today, however, this zone begins finally to be resolved in observations from space with the Hubble Space Telescope (HST) and from the ground with the 8m-class telescopes provided with Adaptive Optics. Both systems work at 0.”05 - 0.”1 angular resolution, that corresponds to 7 - 14 AU in Taurus. The real ‘core’ of the acceleration engine, however, that lies below the so-called ‘Alfvén surface’ located at a height of a few AUs above the disk, is still out of reach of current instrumentation, and will only be approached with VIS / NIR interferometry. Nevertheless, precious information on the launch mechanism can already be gathered form the observation with HST of the portion of the jet immediately above the acceleration zone, that is the region from 10 to 100-200 AU above the disk. In this contribution I will describe the observational results recently acquired this way, and the constraints that they impose to the models. A quick sketch if the capabilities offered by VIS/NIR interferometry willl also be presented in the last Section.

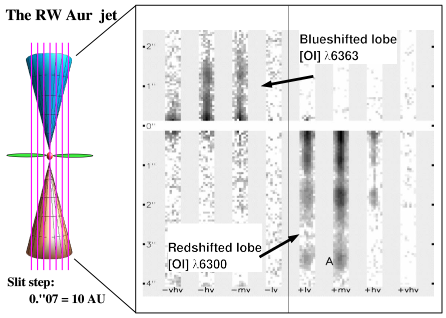

Fig. 1. Structure of the bipolar jet from RW Aur in four different “channel maps”, at low, moderate, high and very high velocity (lv, mv, hv and vhv resp., up to $|v_{rad}| \sim 320$ km s^{-1}), derived from HST/STIS spectra at 0.″1 resolution (Woitas et al. 2002).

2. Morphology and excitation properties in the initial jet channel

The structure of a number of TTSs jets in their initial portion has been derived from the analysis of multiple spectra taken with the Space Telescope Imaging Spectrograph (STIS) on board HST. Differently from their extragalactic counterparts, jets powered by young stars have a spectrum characterised by a rich variety of permitted and forbidden lines, with almost no continuum. This allows one to apply a full set of standard and specialised diagnostic techniques for the study of line ratios, that provide a big wealth of information about the physical nature of the gas (excitation conditions, velocity, relative abundances..). Although STIS works with moderate spectral resolution in the optical (R ∼ 6000), the combination of its capabilities with HST high angular resolution have literally flooded us with new and important information. In fact with HST jets are resolved *transversely* across their width (∼ 0.″5), so that one can investigate the variation of physical quantities both along and across the flow.

For example, we have observed the jets from the TTSs RW Aur and DG Tau with multiple exposures of the 0.”1 STIS slit, stepping the slit position across the flow every 0.”07 (see Fig. 1, left). In this way we have built 3-D cubes of data (2-D in the spatial directions and 1-D in radial velocity) to study in detail a region very close to the disk, in which the jet properties are still dictated by the launch mechanism. One immediate application is the reconstruction of 2-D images of the jets in different velocity intervals. Examples of such ‘channel maps’ are shown in Fig. 1 for the bipolar flow from RW Aur (Woitas et al. 2002) . Typically, the jets show an onion-like kinematic structure (Bacciotti et al. 2000), being more collimated at higher velocities and excitation. Also, the diameter of the flows at the observed height above the disk, measured as the Full Width Half Maximum of the transverse emission profile in the reconstructed images, is about a few tens of AU at the jet base, and collimation is

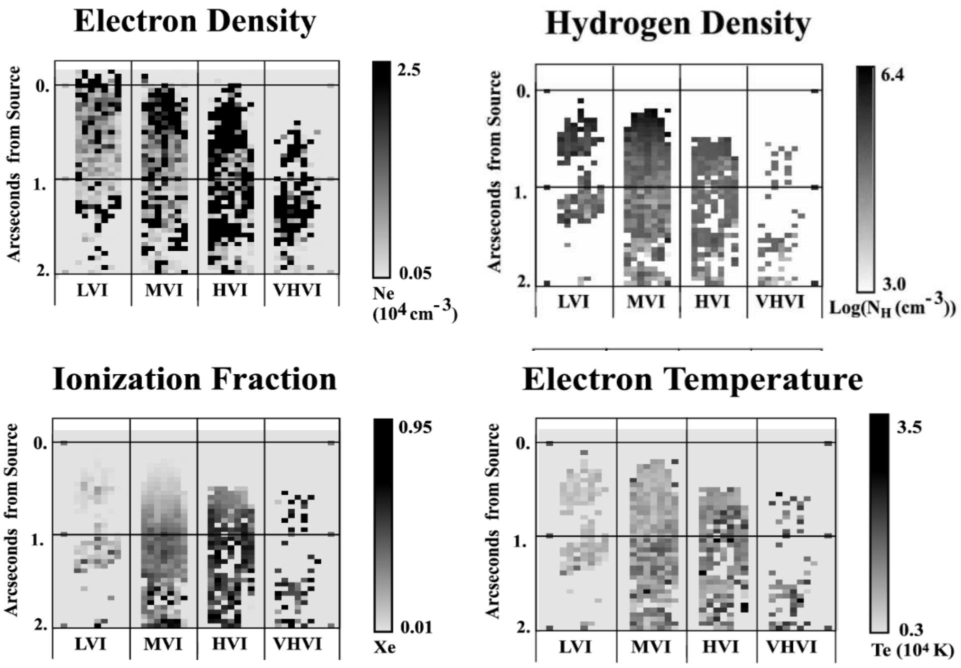

Fig. 2. 2-D maps of the physical conditions of the gas in the DG Tau jet in four velocity intervals (low, moderate, high and very high velocity) obtained from STIS multi-slit spectra (Bacciotti 2002).

achieved very early, within at most 10 - 20 AU from the source. These properties are indeed predicted by the magneto-centrifugal launch models.

The maps of the line ratios constructed with STIS can then give information about the gas physics, using well-tested spectroscopic diagnostic techniques. In this way we have obtained 2-D maps of the various quantities of interest in the different velocity channels, as shown in Fig. 2 for the blueshifted DG Tau jet. The obtained electron density (n_e) maps, for example, confirm that n_e is higher closer to the star, the axis, and at higher velocity (Bacciotti et al. 2004).

The interesting parameter to compare with model predictions is, however, the total hydrogen density n_H. The so-called 'BE' diagnostic technique, developed by our group some years ago (see, e.g., Bacciotti 2002), allows us to estimate, along with the electron temperature T_e, the hydrogen ionization fraction x_e, that combined with n_e gives n_H. In the jet, one typically finds $0.02 < x_e < 0.6$, and total densities between 10^4 and 10^6 cm^{-3}. In the same region $8\ 10^3 < T_e < 2\ 10^4$ K. These values can be compared with the predictions of magnetic models, as it has been done, for example, in Garcia et al. (2001) and Shang et al. (2002).

Finally, from the values derived for n_H, the jet diameter and the de-projected velocity, one can determine one important parameter for the jet launch theory, the mass flux in the jet $\dot{M}_{\rm jet}$. Our estimates indicate values for this quantity of about 10^{-7} M$_\odot$ yr^{-1}, the colder and slower external layers of the jet contributing the most (Bacciotti et al. 2004). According to magneto-centrifugal models, $\dot{M}_{\rm jet}$ should be about 5 - 10 % of $\dot{M}_{\rm acc}$, the mass accretion rate through the disc onto the central object. Our observations confirm this prediction in all the cases studied (e.g. Woitas et al. 2002).

3. Jet rotation, and constraints for the models

As described in the Introduction, nearly all the proposed models invoke rotation of the star/disk/jet system as a necessary element to accelerate the flow. Therefore, if models are correct some trace of rotation should be observable in the outflow. Hints of rotation were first found in the HH 212 jet at large distance (10^4 AU) from the source by Davis et al. (2000). This location, however, is too far from the star to discriminate if the rotation is induced by the acceleration mechanism or by the interaction with the ambient. To test the launch models one has to search for rotation in the region immediately above the disk (less than 100 AU from the star), which is now accessible by HST/STIS. To this aim, we have recently conducted a number of studies to determine if stellar jets rotate at their base.

Firstly, we detected rotation in the flows from DG Tau and RW Aur, during the analysis of the sets of 'parallel' spectra described in the previous Section (Bacciotti et al. 2002, Woitas et al. 2004). Systematic differences in the radial velocity of about 6 to 20 ± 7 $\mathrm{km\,s^{-1}}$ were found for each pair of slits displaced symmetrically with respect to the axis (see Fig. 3, left panel).

We have then started a search for rotation signatures in a number of other well-known jets, in the ultraviolet, optical and near-infrared wavelength ranges, with HST/STIS and with ISAAC at the ESO Very Large Telescope (VLT). For this survey we have chosen to position the slit *across* the jet beam, which gives a much higher efficiency in both observation and data reduction. An example, for the flow from Th 28, is given in Fig. 3, right panel. The skew in lower order contours of the line flux is consistent with the presence of rotation in the outer jet channel. The displacement in wavelength at the jet borders gives the Doppler velocity differences across the flow, which is again about 10 - 25 ± 5 km $\mathrm{s^{-1}}$ at 50 - 60 AU from the source and 20 - 30 AU from the axis (Coffey et al. 2004). In summary, rotation has been found in all the targets examined, and cross-checked to be consistent in the various elements of the system (bipolar lobes, disk) and between different datasets. Rotation thus seems to be a general property of stellar jets, as it was expected if the magneto-centrifugal mechanism is to generate the jets.

It is now interesting to discuss what these measurements tell us about the details of the models. First, we find that the observed toroidal velocities are in agreement with model predictions for the observed location in the flow. Secondly, from the toroidal velocities one can estimate of the *"footpoint radius"* of the wind, i.e. the location in the disk from where the observed portion of the rotating wind is launched. In all cases examined the observations are consistent with the footpoint being located between 0.5 and 2 AU from the star (Bacciotti et al. 2002, Anderson et al. 2003, Coffey et al. 2004, Pesenti et al. 2004). This finding appears to support the disk-wind models, that consider an extended region in the disk for the origin of the wind, although X-winds are not to be ruled out, as they may constitute the inner axial region of the wind.

Using then mass and angular momentum conservation in the global system, we have also verified that a consistent fraction of the excess disk angular momentum (from 70 to 100 %) can be carried away by the jet. This also indicates that disk viscosity, whose nature is still unidentified, plays anyhow a minor role in the angular momentum balance (Woitas et al. 2004). By-products of these calculations are the estimates of the ejection efficiency and of the magnetic lever arm necessary to accelerate the matter at the observed velocities.

Finally, in the framework of magnetocentrifugal models, the sum of kinetic angular momentum and toroidal field tension is conserved along the flow motion (Ferreira 2002). Since we know the kinetic contribution, we can estimate the intensity of the toroidal magnetic field B_ϕ in the jet, a quantity that cannot be measured directly, despite its crucial importance for the collimation of the jet (the expected Zeeman splitting is much smaller than the width of the lines in the optical and NIR ranges). We find that $B_\phi < 6$ mG. This upper limit is 3/2 the value obtained imposing equipartition between thermal and magnetic

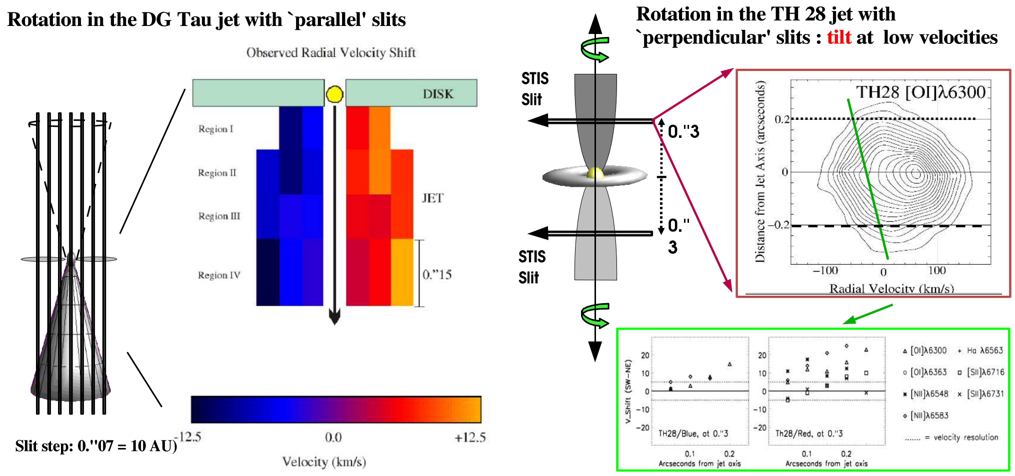

Fig. 3. Left: the Doppler velocity shifts in the line profiles observed with HST/STIS ‘parallel’ stepped slits give rise to a 2D ‘spin map’in the blue lobe of the DG Tau jet (Bacciotti et al. 2002). Right: ‘perpendicular slit’ observations of the jet from Th 28 reveal rotation as a skew (oblique line) in the line position-velocity diagram. The velocity shifts are measured in various lines at mirrored positions with respect to the jet axis (bottom right, Coffey et al. 2004).

pressures, an assumption often used in numerical simulations. We thus see that even if we are not probing the central engine yet, the high angular resolution observations with HST/STIS already give many useful constraints on the proposed models.

4. The future: VIS/NIR interferometry with VLTI and LBT

The final confirmation of the magneto-centrifugal scenario is expected to come from the planned observations with interferometric techniques. The main facilities that are being built for VIS/NIR interferometry are the VLT Interferometer (VLTI) at ESO-Paranal, and the Large Binocular Telescope (LBT) at Mount Graham in Arizona.

A joint project by several European Institutes will examine, using guaranteed time at the VLTI spectrograph AMBER, the morphology and kinematics of the jets from bright southern TTSs (see Fig. 4, and Bacciotti et al. 2003). With the VLTI resolution of 1 mas we will be able to access the innermost part of the flow down to 0.1 AU. We thus will be

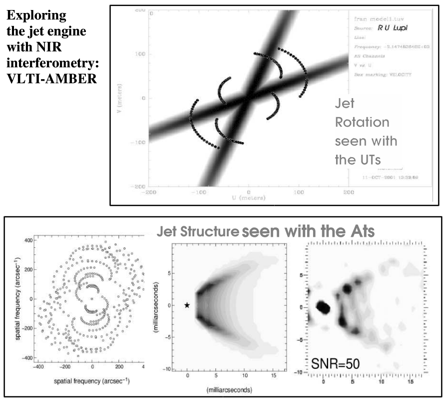

Fig. 4. Planned VLTI observations of the jet acceleration region: Fourier Plane coverage for measurements using the 8m Unit Telescopes (UTs) (top) and the auxiliary telescopes (ATs) (bottom), with model of the jet shape and image simulation (Bacciotti et al. 2003).

able to access the region below the the Alfvén surface, where according to the models the flow attains most of its vertical velocity, and the jet collimation is set in place. Similarly, the Large Binocular Telescope Interferometer (LBTI) with its two 8.4 meter mirrors will allow to investigate at 2 mas resolution a larger fraction of the conjugate Fourier plane than with VLTI, which will permit a better rendering if the reconstructed jet images (Herbst 2003). With these instruments we foresee to finally enter the "core" of the central engine, and test conclusively the many models developed by theoreticians against "Real" jets observed in the sky.

Acknowledgements. Based on observations made with the NASA/ESA *Hubble Space Telescope*, obtained at STScI, which is operated by AURA, Inc., under NASA contract NAS5-26555

References

Anderson, J. M., Li, Z.-Y., Krasnopolsky, R., Blandford, R., 2003, ApJ, 590, L107
Bacciotti, F., R. Mundt, T.P. Ray, J. Eislöffel, J. Solf, M. Camenzind., 2000, ApJ, 537, L49
Bacciotti, F., 2002, in Emission Lines from Jet Flows, eds. W.J. Henney, W.Steffen, A.C. Raga, L. Binette, RMxAC, 13, 8
Bacciotti, F., Ray, T.P., Mundt, R., Eislöffel, J., Solf, J., 2002, 576, 222
Bacciotti, F., Testi, l., Marconi, A., Garcia, P.J.V, et al., 2003, Ap&SS, 286, 157
Bacciotti, F., J. Eislöffel, T.P. Ray, R. Mundt, J. Solf, 2004, A&A (in preparation).
Coffey, D., Bacciotti, F., Ray, T.P., Woitas, J., Eislöffel, J., 2004, ApJ, 604, 758
Davis, C. J., Berndsen, A., Smith M. D., Chrysostomou, A., Hobson, J., 2000, MNRAS, 314, 241
Ferreira, J., in Star Formation and the Physics of Young Stars eds. J. Bouvier and J.-P. Zahn, (EDP Sciences), 2002, Vol. 3, p. 229
Garcia, P., J. Ferreira, S. Cabrit, and L. Binette, 2001, A&A, 377, 589
Herbst, T., 2003, Ap&SS, 286, 45.
Königl, A. & Pudritz, R., 2000, in Protostars and Planets IV, eds. V. Mannings, A. P. Boss, S. S. Russell (Tuscon: Univ. Arizona Press), 759
Pesenti, N., Dougados C., Cabrit S., Ferreira J., O'Brien D., Garcia P., A&A 416,
Reipurth, B., Bally, J. 2001, ARA&A, 39, 403
Shang, H., Glassgold, A. E., Shu, F. H., Lizano, S., 2002, ApJ, 564, 853
Shu, F. H., Najita, J. R., Shang, H., Li, Z.-Y., 2000, in Protostars and Planets IV, eds. V. Mannings, A. P. Boss, S. S. Russell (Tuscon: Univ. Arizona Press), 789
Woitas, J., T.P. Ray, F. Bacciotti, C.J. Davis, J. Eislöffel, 2002 ApJ 580, 336
Woitas, J., Bacciotti, F., Ray, T.P., Eislöffel, J., Marconi, A., Coffey, D., A&A, 2004, submitted