Mem. S.A.It. Vol. 76, 366
© SAIt 2005

Memorie della

The accretion/ejection paradigm of low mass stars tested with HST

F. Bacciotti[1], T.P. Ray[2], J. Eislöffel[3], J. Woitas[3] and D. Coffey[2]

[1] INAF-Osservatorio Astrofisico di Arcetri, L.go E. Fermi 5, 50125 Firenze, Italy; e-mail: `fran@arcetri.astro.it`
[2] School of Cosmic Physics, Dublin Institute for Advanced Studies, 5 Merrion Square, Dublin 2, Ireland
[3] Thüringer Landessternwarte Tautenburg, Sternwarte 5, D-07778 Tautenburg, Germany

Abstract. In the last few years new investigation techniques have allowed us to study in depth the spectacular phenomenon of protostellar jets, and to test the validity of the proposed models for their acceleration. In this contribution we review the current knowledge on the subject, with a special emphasis on the recent achievements obtained thanks to observations at high angular resolution, like those performed at subarcsecond scales with the Hubble Space Telescope.

These results have made us able to define more clearly the morphology, kinematics, excitation of the flows on small scales, and, in turn, to derive stringent constraints for the physical processes at work. The novel information acquired puts us in a very good position to plan theoretical and observational studies aimed at understanding if similar accretion/ejection processes are also at work during the formation of Brown Dwarfs. If scaled-down versions of Herbig-Haro jets are found associated to these objects, then it would mean that the well-known formation scenario of solar–mass stars is truly universal.

Key words. ISM: jets and outflows – Stars: Formation – High angular resolution

1. Introduction

Many studies have been dedicated recently to the definition of the most likely mechanism for the formation of low mass stars. A general consensus has been reached about the fact that the formation scenario includes accretion of matter from a disk onto the central object, as well as expulsion of a part of the accreting material in bi-polar winds. Both accretion and ejection have indeed been observed around young stellar objects, and in particular in T Tauri stars. For example, the 'veiling' of stellar photospheric lines is due to the radiation produced at the accretion shock (Hartigan et al. 1995), and the complex profiles of permitted lines such as Hα and HeIλ6678 are interpreted as signatures of accretion (Muzerolle et al. 2001). To observe matter expelled at high velocity is paradoxically even easier. This takes the form of wide-angle winds, highly collimated supersonic jets and associated molecular outflows (Reipurth & Bally 2001, Eislöffel et al. 2000). Actually, the interplay between accretion and ejection is believed to be a fundamental step

---

Send offprint requests to: F. Bacciotti

Correspondence to: Largo E. Fermi 5, 50125 Firenze

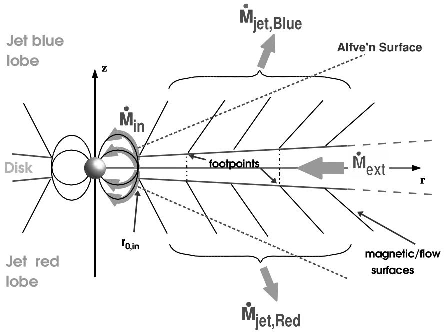


Fig. 1. Sketch of the accretion/ejection region around a forming low-mass star according to the disk-wind scenario. The configuration of the flow/magnetic surfaces is indicated by the oblique solid lines attached to the inner section of the accretion disk. The thick grey arrows indicate the mass flows (adapted from Woitas et al. (2004)).

of the formation mechanism. According to the most widely accepted theory, jets are launched by the combined action of magnetic and centrifugal forces along the magnetic field surfaces rooted in the vicinity of the star (within 0.1 AU for the *X-wind*, Shu et al. (2000) or within 1-10 AU for the *disk-wind*, e.g. Königl & Pudritz (2000), Ferreira (2002)). The magnetic field back-reacts braking the disk rotation, so that the flow actually ’extracts’ and transports away some angular momentum from the system. In this way the matter in the disk can flow inward and finally accrete onto the central star (see fig. 1).

It is not clear, however, if such a mechanism applies also to Brown Dwarfs (BDs), the ’failed’ stars with $0.013M_\odot \leq M \leq 0.075M_\odot$ that do not reach central temperatures high enough to ignite hydrogen burning (Basri, 2000). The presence of accretion onto BDs is suggested by their spectral energy distributions (Natta et al. 2002) and high resolution optical spectra (Jayawardhana et al. 2004; Natta et al. 2004).

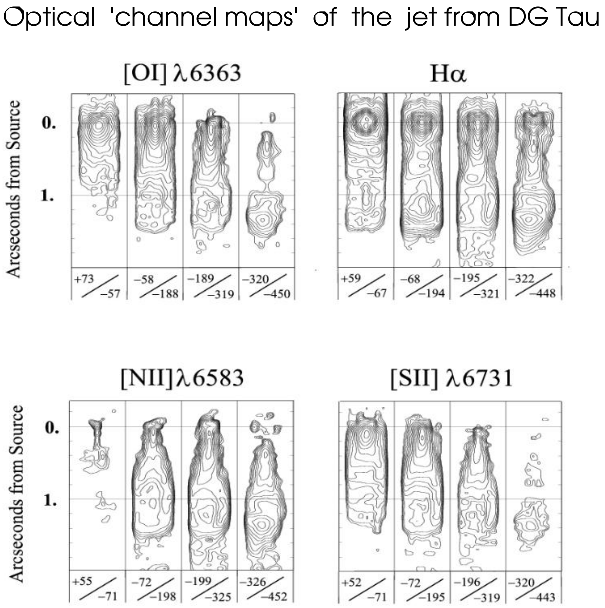
But do they have outflows ? Optical forbidden emission lines (FELs) typical of classic stellar jets have been found in some BD spectra (Comerón et. al. 2003), which, however, does not constitute yet a proof of the existence of collimated outflows. More conclusive evidences of jets around BDs are actively being searched for at the time of writing (Whelan et al. 2004, and see the contributions by T. Ray and S. Mohanty in this volume). If such outflows are found, this would underscore the universality of the accretion/ejection mechanism during star and brown dwarf formation.

To aid the search of jets from sub-stellar mass objects, and to examine the implications of a positive detection for the characterisation of BDs, it is useful to review the current knowledge about the origin of collimated jets powered by T Tauri stars. In this contribution we illustrate the recent observational results obtained at high angular resolution with the Hubble Space Telescope (HST), and the constraints that they impose to the models.

2. Properties of a jet in the acceleration/collimation region

Jets powered by young stars have a spectrum characterised by a rich variety of emission lines in the optical and Near Infrared (NIR) wavelength range. This allows one to apply specialised spectroscopic diagnostic techniques, that provide a big wealth of information about excitation conditions, velocity, relative abundances, etc.. We have been able to observe the initial portion of jets accelerated by T Tauri stars with the spectrograph STIS on board HST, that worked at 0.”05 - 0.”1 angular resolution in the optical (7 - 14 AU in Taurus). The real ‘core’ of the acceleration engine actually lies below the so-called ‘Alfvén surface’, located at a height of a few AUs above the disk (see fig. 1). This zone will only be reached with NIR interferometry, but precious information on the launch mechanism can already be gathered from HST observations of the region immediately above, that is the region from 10 to 100-200 AU above the disk, as illustrated in the following.

Although STIS worked with only $R \sim 6000$ in the optical, the combination with HST high angular resolution gave new and important information, as jets could be resolved transversely. For example, we have observed the jets from the TTSs RW Aur and DG Tau with mul-



Optical 'channel maps' of the jet from DG Tau

Fig. 2. 2-D velocity 'channel maps' of the blue-shifted jet from DG Tau reconstructed from HST/STIS multi-slit optical spectra. The maps illustrate the morphology of the jet in the first 200 AU from the source in various emission lines and in four velocity intervals (low, moderate, high and very high velocities, indicated in km s^{-1}). The jet shows an onion-like structure, as predicted by magneto-centrifugal launch models (adapted from Bacciotti et al. 2004).

tiple exposures of the 0.”1 STIS slit, stepping the slit position across the flow every 0.”07. In this way we have built 3-D cubes of data (2-D spatial, 1-D in velocity) to study in detail the region of interest. One projection of the datacubes gives 2-D images of the jets in different velocity intervals, similarly to the ‘channel maps’ of radio interferometry. An example is shown in Fig. 2 for the blueshifted flow from DgTau (Bacciotti et al. 2000, Bacciotti et al. 2004). The jet shows an onion-like kinematic structure, being more collimated at higher velocities and excitation.

Generally, 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 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, by applying to them various spectral diagnostic tools. In this way we have obtained 2-D maps of the various quantities of interest in the different velocity channels (Bacciotti 2002). 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 (Bacciotti & Eislöffel 1999), 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. At the jet base, 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 (Garcia et al. 2001; Shang et al. 2002).

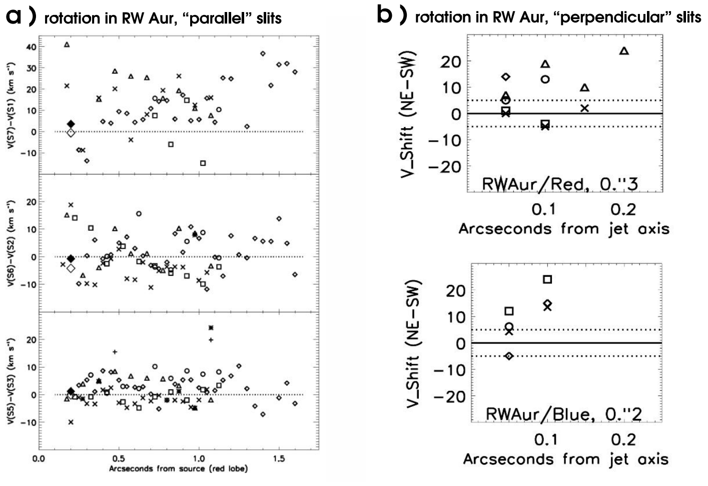
Finally, from n_H, the jet diameter and the de-projected velocity, one can determine the mass flux in the jet $\dot{M}_{\rm jet}$, that we find to be of the order of 10^{-7} M$_\odot$ yr^{-1}, with the colder and slower external layers of the jet contributing the most. According to magneto-centrifugal 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: what does it tell us about the launch mechanism ?

According to the magneto-centrifugal scenario a key element to accelerate the flows is the rotation of the system. Since the mechanism predicts that the jet carries away the excess angular momentum, some trace of rotation should be observable in the outflow immediately above the accelerating region. After the first hints of rotation seen in the HH 212 jet at large distance (10^4 AU) from the source by Davis et al. (2000), no other detection of rotation has been reported, up to our measurements of the initial jet channel made with STIS. 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 km s^{-1} were found for each pair of slits displaced symmetrically with respect to the axis (see Fig. 3, left panel). Then, rotation signatures have been found in a number of other jets, in the ultraviolet and optical lines, with the slit placed *across* the jet beam (Coffey et al. 2004). An example of the results of rotation studies in both observing modes is given in Fig. 3, for the bipolar flow from RW Aurigae: both sets of data are consistent with the presence of rotation at the borders of the jet channel, in the same rotation sense. In our survey, 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 (Testi et al. 2002)), and between different datasets. Typical Doppler velocity differences across the jets are about 10 - 25 ± 5 km s^{-1} at 50 - 60 AU from the source and 20 - 30 AU from the axis (Coffey et al. 2004). Rotation thus seems to be a general property of stellar jets, with velocity values in agreement with the magneto-centrifugal mechanism.

It is now interesting to discuss what more these measurements tell us about the launch mechanism. From the combination of measured toroidal and poloidal 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 (cfr. Fig. 1). 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 may be present inside, closer to the symmetry axis. Using then mass and angular momentum conservation in the global system, we have verified that a consistent fraction of the excess disk angular momentum (60% or more) 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 of the inner regions of the disk (Woitas et al. 2004). By-products of these calculations are the ejection efficiency and the magnetic lever arm of the system.

Finally, in the framework of magnetocentrifugal models, the poloidal and toroidal components of the magnetic field (that cannot be measured directly for stellar jets) are related to the corresponding components of the velocity field. Using this property one finds that at the observed location the toroidal component of the magnetic field is 3 - 4 times larger than the poloidal component (Woitas et al. 2004). A prevalence of the toroidal field component above the Alfèn surface is indeed predicted by the models, that attribute to a magnetic 'hoop



a) rotation in RW Aur, “parallel” slits

b) rotation in RW Aur, “perpendicular” slits

Fig. 3. HST/STIS observations of the line velocity shifts across the bipolar jet from RW Aur with **a)** multiple slits parallel to the jet axis (Woitas et al. 2004) and **b)** slits perpendicular to the jet axis (Coffey et al. 2004). The velocity gradient across the jet is consistent with rotation of the gas around the symmetry axis. The values are in agreement with the predictions of the magneto-centrifugal models (Pesenti et al. 2004).

stress’, the collimation of the flow (Königl & Pudritz 2000).

4. Conclusions: accretion/ejection in Brown Dwarfs

Even if current observational capabilities do not yet resolve directly the accretion/ejection region of low-mass stars, the results collected with HST/STIS in the last few years all point toward a confirmation of a disk-wind magneto-centrifugal scenario. The proposed models are not strongly dependent on the mass of the central star, unless the latter produces too strong ionizing photon flux.

We may then speculate that the same processes can apply to both T Tauri stars and Brown Dwarfs. This gives us useful constraints for what we expect to find for a jet from a BD. If the same magnetocentrifugal mechanism is to apply, for example, the mass flux rate in the outflow scales with 1/100 to 1/10 of the mass accretion rate, which has been measured already in several BDs (Natta et al. 2004). From the mass flux rate one can in turn estimate the radiation flux expected for the BD jet in lines such as Hα and [OI]λ6300 (see e.g. Masciadri & Raga 2004, Whelan et al. 2004, and the contribution by T. Ray in this volume).

Finally, a confirmed detection of outflows from BDs would have interesting implications for the origin of these sub-stellar objects, as the case for a star-like formation with a durable T Tauri phase would be strengthened, in opposition to the formation scenario in which the BD is ejected from a multiple system.

Acknowledgements. The authors wish to thank the organisers for the invitation to present these results, which are based on observations by NASA/ESA *Hubble Space Telescope* (STScI, AURA, contr. NAS5-26555).

References

Anderson, J. M., Li, Z.-Y., Krasnopolsky, R., Blandford, R., 2003, ApJ, 590, L107

Bacciotti, F. & Eislöffel, J., 1999, A&A 342, 717

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., J. Eislöffel, T.P. Ray, R. Mundt, J. Solf, 2004, in prep.

Basri, G., 2000, ARA&A 38, 485

Coffey, D., Bacciotti, F., Ray, T.P., Woitas, J., Eislöffel, J., 2004, ApJ, 604, 758

Comerón et. al. 2003, A&A 406, 1001

Davis, C. J., Berndsen, A., Smith M. D., Chrysostomou, A., Hobson, J., 2000, MNRAS, 314, 241

Eislöffel, J. et al., 2000, in Protostar and Planets IV, eds. V. Mannings, A. P. Boss, S. S. Russell (Tuscon: Univ. Arizona Press), p. 815

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

Hartigan, P., Edwards, S., Ghandour, L., 1995, ApJ, 452, 736

Königl, A. & Pudritz, R., 2000, in Protostars and Planets IV, eds. V. Mannings, A. P. Boss, S. S. Russell (Tuscon: Univ. Arizona Press), 759

Jayawardhana, R., Mohanty, S., & Basri, G., 2003, ApJ, 592, 282

Masciadri, E., Raga, A.C., 2004 ApJ, 615, 850

Muzerolle, J., Calvet, N., Hartmann, L., 2001, ApJ 550, 944

Natta, A. et al. 2002, A&A 393, 597

Natta, A. et al. 2004, A&A, 424, 603

Pesenti, N., Dougados C., Cabrit S., Ferreira J., O'Brien D., Garcia P., A&A 416, L9

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

Testi, L., Bacciotti, F., Sargent, A. I., Ray, T. P., Eislöffel, J., 2002, A&A 394 L31

Whelan, E., Ray, T.P., Bacciotti, F., Natta, A., Testi, L., Randich, S., 2004, in prep.

Woitas, J., T.P. Ray, F. Bacciotti, C.J. Davis, J. Eislöffel, 2002 ApJ 580, 336

Woitas, J., Bacciotti, F., Ray, T.P., Marconi, A., Coffey, D., Eislöffel, J., A&A, 2004, in press