SF2A 2009
M. Heydari-Malayeri, C. Reylé and R. Samadi (eds)

MAGNETIC JETS FROM YOUNG STARS: HIGH-ANGULAR RESOLUTION OBSERVATIONS

Dougados, C.[1]

Abstract. Supersonic jets are one of the most spectacular manifestation of the formation of a young star. Although their connection with magnetic processes is well established, the exact origin of jets is still a major open issue in star formation. I review in this contribution constraints on magnetic jet launching models derived from high-angular resolution observations of the inner 100 AUs in T Tauri winds. I then discuss open questions and future directions in jet studies, in particular the expected contributions of near-infrared and radio interferometry (with the second generation VLTI instrumentation and ALMA/NOEMA).

1 Introduction

Jets are observed at all phases of stellar formation where active accretion occurs (i.e. for ages less than a few Myrs). The physical mechanism by which mass is ejected from young stars and collimated into jets still remains a fundamental open issue. In addition to injecting mechanical energy at large scales, jets may play a crucial role in the regulation of the angular momentum and the final mass of the forming protostar. Moreover, as I will detail below, proto-stellar jets provide indirect constraints on the central Astronomical Units (AU) of the young star-disc system, still largely unaccessible to direct observations, which are critical regions for planet formation models. Jets from young stars, because of their proximity, offer a unique opportunity to investigate the accretion/ejection mechanisms at unprecedented angular resolution.

The supersonic ejection velocities (Mach number $V_j/C_s \simeq 30$), the cylindrical collimation achieved very close to the central source ($z < 30-50AU$) and the large ejection efficiencies observed (mass ejection to accretion rate ratios $\simeq 0.1$) can all be accounted for by accretion driven magneto-hydrodynamic wind models. A large scale magnetic field, anchored in a central rotating object, provides natural auto-collimation through the Lorentz force generated by the azimutal B_ϕ. Three classes of steady MHD wind models have been extensively studied. They differ by their launching region: either the magnetic field lines are anchored at the stellar surface (see for e.g. Sauty et al. 2002), in the inner regions of the accretion disc (Ferreira 1997), or at the interface between the stellar magnetosphere and the accretion disc (X-wind, Shu et al. 1994). These different origins have distinct implications for the magnetic structure and angular momentum regulation of the inner star-disc system. Steady disc wind solutions require in particular an equipartition magnetic field (with magnetic pressure comparable to thermal pressure) in the inner regions of the disc (r < a few AUs). This required magnetisation of the inner disc would then have strong implications on planetary formation models. The star-disc interaction is also the probable source of sporadic mass-loss, including coronal mass ejections. However, this mass-loss would require an external collimation agent. See Ferreira et al. (2006) for a thorough discussion of the different possible sources of mass-loss in young stars.

I first summarize in this contribution major results from high-angular resolution studies of the launching regions of proto-stellar jets, obtained my myself and collaborators, especially within the context of the Research and Training Network JETSET. I then discuss most recent developments and future directions.

2 Microjets from T Tauri stars: optical and near-infrared high-angular resolution studies

T Tauri stars are optically revealed pre-main sequence stars with ages of $\simeq 10^6$ yrs that have already emerged from their native environment. They are however still actively accreting matter from circumstellar discs and

---

[1] Laboratoire d'Astrophysique de Grenoble, UMR 5571, BP 53X, F-38041 Grenoble Cédex 9

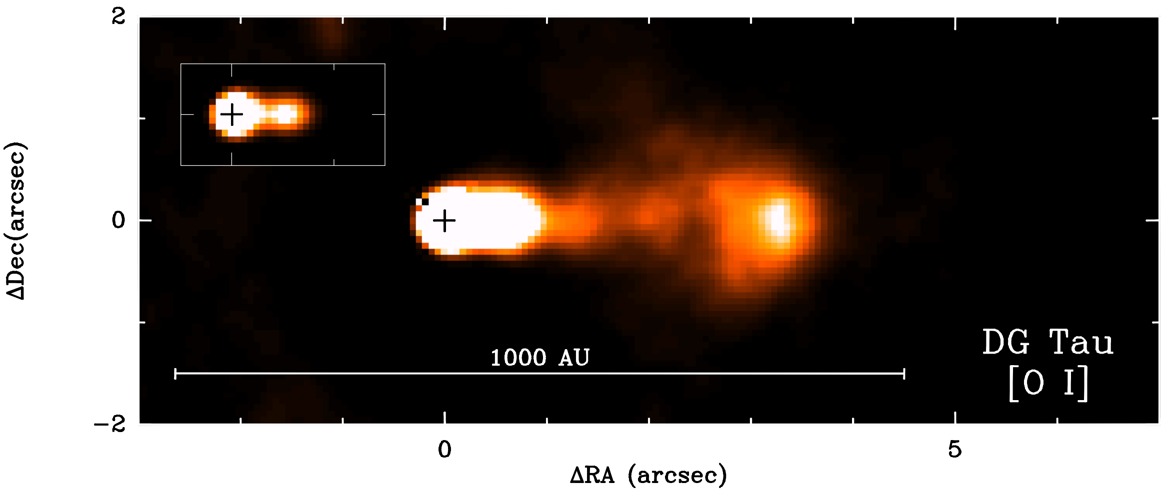

Fig. 1. Deconvolved [O I]λ6300Å+ continuum narrow band image of the DG Tauri jet obtained with the PUEO Adaptive optics system on the Canada-France-Hawaii telescope. The spatial resolution achieved is $0.1''$. Insert (*top left*) is a high-contrast image near the source. Figure adapted from Dougados et al. (2000).

driving small-scale jets (see Fig. 1). Although less powerful than the HH flows driven by the younger embedded protostars, T Tauri jets give direct observational access to the innermost collimation and acceleration regions of the wind ($z \leq$ a few 100 AUs), allowing to derive meaningful constraints to launching models.

Protostellar jets radiate a wealth of emission lines in the optical and near-infrared domains, tracing a partially ionized plasma at temperatures T $\simeq 5\times10^3$-10^4 K, characteristic of post-shock cooling regions. Both HST and adaptive optics on ground-based telescopes allow to reach angular resolutions of $\simeq 0.1''$, corresponding to 14 AU at the distance of the Taurus star forming cloud. High-angular resolution techniques have been recently combined with spectro-imaging instruments allowing to reach spectral resolutions ranging between 3000 and 10000 (velocity resolution between 30 and 100 km s^{-1}). To date, $\simeq$ 15 jets from T Tauri stars have been mapped in the optical and near-infrared domains with such instrumentation (see Ray et al. 2007 for a review). I review below the observed excitation conditions, morphological and kinematical properties of the atomic component in the central regions of the jets.

• Jet widths and collimation: In Ray et al. (2007) we compile all available jet widths measurements derived on scales less than 200 AU from the driving source. Beyond $z \simeq 50$ AU, close to cylindrical collimation is achieved with semi-opening angles consistent with thermal radial expansion ($tan(\theta) = C_s/V_j$). Current constraints on the launching region of the atomic component is r < 3 AU.

• Kinematics: Terminal velocities of 200-400 km s^{-1}, 2-3 times the escape velocity of the central star, are reached within 20 AU from the central source. Some jets, like the one from DG Tauri, present a shell of material at intermediate velocities (30-200 km s^{-1}) which surrounds the more collimated high velocity flow (see e.g. Lavalley-Fouquet et al. 2000). A recent important advance came from the detection in 6 T Tauri jets of velocity gradients across the jet body, indicative of rotation velocities $V_\phi = 5 - 15$ km s^{-1}(Bacciotti et al. 2002; Coffey et al. 2004, 2007). These observations put strong constraints on the launching region (Ferreira et al. 2006, see below). However the observed transverse velocity asymetries may trace other effects than rotation in the jet body. We have launched a program with the Plateau de Bure interferometer to study the connexion between disc and jet rotation. In one case, out of the 3 investigated so far, the sense of rotation in the disc inferred from millimetric observations is opposite to the jet sense of rotation deduced from HST observations (Cabrit et al. 2006). In addition, our near-infrared study of the DG Tauri microjet with SINFONI shows evidence for jet axis precession which could generate velocity asymetries similar to the ones observed (Agra-Amboage et al. in prep).

• Excitation conditions: Estimates of electronic densities, ionisation fractions and temperatures are derived from observed optical and near-infrared line ratios. The onion-like structure of the flow seen in the kinematics is also observed: ionisation fractions and total densities increase with flow velocity (see Ray et al. 2007). Estimates of mass-loss rates give ejection to accretion rate ratios $\simeq 10$ % . Optical and near-infrared line ratios are well reproduced by J-type shock models, with shock velocities $\simeq 20$ % of the flow velocity (see e.g. Lavalley-Fouquet et al. 2000). Internal working surfaces produced by flow ejection veriability on timescales of a few yrs are the most likely source for the observed structures of the flow.

2.1 Implication for jet launching models

Ejection mechanism appear steady on the characteristic dynamical timescales of the inner disc regions. Ferreira et al. (2006) and Cabrit (2007) discuss the implications of the derived atomic jet properties for steady ejection models. In particular in Ferreira et al. (2006), we compute the specific angular momentum in the jet predicted by steady wind solutions. In summary:

1) Stellar wind models predict a very small specific angular momentum in the jet, 2 orders fo magnitude smaller than current observational estimates/upper limits. However, they can account for the observed terminal velocities and for mass-loss rates ≤ 10 % of the accretion rate, provided significant extra energy is deposited at the base of the outflow. Indeed, since T Tauri stars rotate at only 10 % of break-up, centrifugal launching is not very effective and strong pressure gradients are needed to accelerate a wind from the stellar surface. This energy could be extracted from the accretion process but requires a very efficient conversion mechanism.

2) Wide-angle wind originating from the disc co-rotation radius ("X-winds") predict a moderate specific angular momentum, roughly 10 times lower than current observational estimates /upper limits. These models predict a very narrow range of observed terminal velocities and fail to account for the intermediate flow velocities (10-100 km s^{-1}) sometimes observed. It is also not clear how this model would brake down the central protostar and explain its slow rotation rate.

3) Disc winds with moderate magnetic lever arms (Casse & Ferreira 2000) originating from the inner AUs of the accretion disc, succeed in reproducing observed collimation and kinematical properties, including reported rotation signatures as well as observed mass-loss rates. However, these disc wind solutions require heat input at the upper disc surface layers, which origin is still unknwon. In addition, disc winds will not help in braking down the central protostar.

In conclusion, disc winds originating from the inner AUs of the accretion disc seem to reproduce best the ensemble of observational properties of atomic jets. These models require a strong magnetisation of the inner disc ($B = B_{eq} \simeq 0.2G$ at $r_0 = 1AU$), which has a strong implication for the structure of the inner disc (Combet & Ferreira 2008) as well as on planetary formation and migration models in these regions (see e.g Terquem et al. 2003). However disc winds do not solve all current issues, in particular the critical one related to the angular momentum of the central protostar. A stellar wind component may be required to explain the low rotation rates observed for the central object and the hot ($T > 10^5\ K$) outflowing plasma traced by UV lines and X-ray emission (see below). Different components of mass-loss may be present, and contribute in various proportion at different stages of the protostellar evolution.

3 Recent developments and open questions

3.1 Different components of the ejection?

3.1.1 Micro-molecular flows

One recent development has been the detection of micro-molecular flows probed in the near-infrared with the H_2 2.121μm line or in the millimetric domain through the ^{12}CO line. In the two cases studied in details, DG Tauri (Agra-Amboage et al. in prep) and HH 30 (Pety et al. 2006), a slowly expanding ($V < 20$ km s^{-1}) small-scale molecular cavity is detected around the high-velocity atomic jet (Fig. 2). This molecular flow can be naturally explained in the context of the disc wind models. Indeed, Panoglou et al. (2009) have recently shown that streamlines originating from launching radii $r_0 \geq 1$ AU in the disc will remain mostly molecular. The observed properties of these small scale molecular flows (collimation, kinematics) appear compatible with the predictions of a disc wind originating from $r_0 = 1 - 10$ AU, i.e. extending the atomic flow probed with

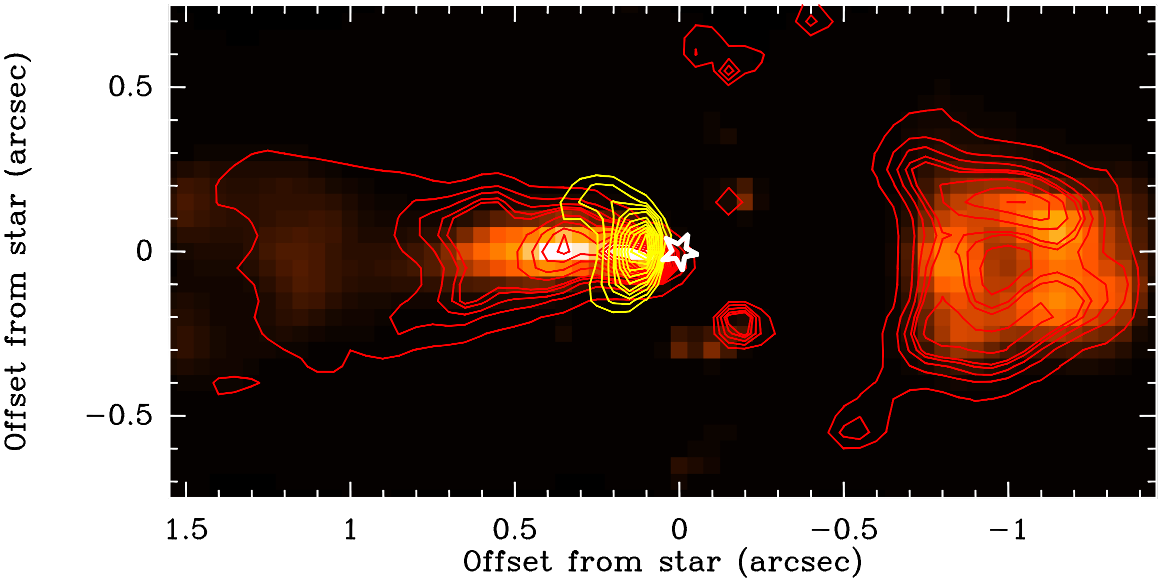

Fig. 2. Composite image of the [Fe II]1.644μm and $H_2$2.212μm emissions in the DG Tau microjet illustrating the nested structure of the flow. . High-velocity [Fe II]1.644μm emission ($V > 150$km s^{-1}) is shown as the background image. Red contours trace the medium-velocity [Fe II] emission ($V < 150$km s^{-1}) and yellow contours the H_2 emission ($V < 50$km s^{-1}). The white cross locates the stellar continuum position. Figure adapted from Agra-Amboage (2009).

optical lines. However, an alternative origin in a photo-evaporated wind cannot be excluded. In that latter scenario, FUV and X-ray radiation from the accretion shock creates a photo-dissociation region on the surface of the disc from which a photo-evaporated wind can originate. This component of mass-loss may play a role in the dispersal of outer disc material.

3.1.2 X-ray emission from jets

Gudel et al. (2007) reported the detection of soft X-ray emission in a few T Tauri stars in addition to the usual absorbed hard X-ray component associated with chromospheric activity. In one case, this emission is spatially resolved and clearly associated with the jet (Gudel et al. 2008). The origin of this high temperature plasma (T = 3.7 10^6 K) in the jet is unclear: it could trace either the high velocity innermost streamlines of a disc wind, or an inner hot and diffuse stellar wind component. Coordinated observing campaigns of the DG Tauri microjet will be conducted this winter combining a deep Chandra imaging and ground-based multi-wavelength spectroscopic studies that will allow to study the relationship between the different mass-loss tracers and hopefully clarify the origin of this MK plasma.

3.2 The influence of the stellar magnetosphere ?

One critical component in our understanding of the star-disc interaction and its role in jet launching and stellar angular momentum regulation is the strength and topology of the stellar magnetic field. As part of the MAPP collaboration led by J.F. Donati a large observing campaign is conducted with the spectro-polarimeter ESPADONS/CFHT aimed at characterizing the topology of the magnetic field in 20 pre-main sequence stars. To date, magnetic topologies for 4 T Tauri stars have been investigated with this method (Donati et al 2007, 2008; Hussain et al. 2009). The inferred magnetic topologies appear strongly correlated with the internal structure of the star (fully convective stars appear to host more simple fields, predominantly dipolar, than partly convective ones). Clearly the sample needs to be increased and the relationship with the jets studied. In parallel to these observational studies, 2D MHD numerical simulations of the star-disc interaction have been conducted in the framework of the JETSET collaboration (Bessolaz et al. 2008; Zanni et al. in press). 3D simulations, necessary to take into account the complexity of the recovered magnetospheres, are currently under development in collaboration between J. Ferreira (LAOG) and C. Zanni (Turin university). In coming years, the combination of these two approaches is expected to lead to significant advances in our understanding of the role of the stellar magnetic field in jet launching and stellar angular momentum regulation.

3.3 Jets across the stellar mass spectrum

Jets have been now identified across the stellar mass spectrum from massive Herbig Ae/Be stars (2-8 $M_\odot$) to brown dwarfs (Whelan et al. 2005, 2007). A detailed study of the microjet from the intermediate-mass star RY Tau (Agra-Amboage et al. 2009) shows properties quantitatively similar to the jets from lower mass T Tauri stars, suggesting a common origin.

4 A Bright Jet future

High-angular resolution studies of jets conducted on spatial scales 10-100 AUs brought significant new constraints to jet launching models. Clearly increasing the sample of sources observed with such techniques is critical to consolidate the conclusions reached so far. Indeed, some critical questions remain open:

1. Do different components of mass-loss contribute (stellar, disc wind, photo-evaporated wind) ? This question can be addressed with a detailed study of the relationship between different mass-loss tracers such as the one conducted in DG Tau.

2. Do all accreting protostars launch a jet and with the same mechanism ? To answer this question a statistical study is critically needed to correlate quantitatively the jet properties (terminal velocity, mass-loss rate, collimation) with the source properties (stellar mass, rotation, magnetic field, disc accretion rate...).

3. What is the evolution of mass-loss through all phases of star formation ?

Clearly, to definitely identify the origin of jets in young stars requires significantly increasing the angular resolution. In this respect, two major facilities are expected to yield significant advance in coming years:

4.1 Probing the central AU: spectrally resolved near-IR interferometry

Near-infrared interferometric instruments such as AMBER on the VLTI now allow to probe milli-arcsecond spatial scales corresponding to 0.1-1 AU at the Taurus distance. With the spectral resolution offered by AMBER (R=1000 and 10000), it now becomes possible to probe the hot gaseous component traced by the HI Brγ line in the very inner regions of young star disc systems. The formation of the HI emission lines in young stars, the most prominent tracer of hot gas, is still unknown: accretion flows, winds, disc atmosphere or a combination of these processes. Preliminary observations of a sample of young massive stars (Herbig Ae/Be stars) showed that the Brγ line emitting region is located between the stellar magnetosphere and the dust sublimation radius (Tatulli et al. 2007; Kraus et al. 2008). In collaboration with M. Benisty & F. Bacciotti (Arcetri Obs., Italy), we have launched observing programs with AMBER/VLTI of a selection of young stars, associated with large scale jets, aimed at: 1) spectrally resolved interferometric observations at R=10000 resolution and 2) imaging interferometry with large UV coverage of the Brγ line emitting region. These observations will provide the first direct constraints on the gaseous component on scales < 1 AU, ie the launching regions of jets.

4.2 Jets from younger protostars: NOEMA and ALMA contributions

Another major contribution to jet studies is expected from NOEMA and ALMA. With ALMA it will be possible to conduct detailed morphological and kinematical studies of the collimation and acceleration regions of the youngest jets (ages $\leq 10^5$ yr), similar to what is conducted in the optical/near-infrared for T Tauri jets. This will allow to study for the first time the secular evolution of jet properties, in particular collimation, as illustrated by the pioneering study with IRAM/PdBI of the very young HH212 jet (age $\simeq 10^4$ yr) by Cabrit et al. (2007). This study showed that the collimation properties of this very young jet are similar to the ones of the more evolved T Tauri jets, suggesting both that the environment does not play a significant role in jet collimation and that the same mechanism is at play throughout all stages of star formation. With ALMA we will conduct detailed studies of a few selected jets. With NOEMA it will be possible to conduct for the first time a statistical study of embedded young jets allowing to correlate their properties with the properties of their parent molecular cores (angular momentum, magnetic field, core mass).

In conclusion, I believe we stand now at a crossroads in jet studies from the observational as well as from the modelling point of view. On one hand, a wealth of new cutting-edge observations will soon become available: from stellar magnetic field mapping (with ESPADONS and SPIROU), to constraints on the jet launching zone (especially from 2d generation VLTI imaging instruments such as PIONEER, GRAVITY, VSI), and out to the scales of jet collimation and acceleration (with ALMA and NOEMA in the millimetric domain and existing and planned spectro-imaging instruments like MUSE/VLT and JWST/NIRSPEC in the optical/NIR). On the other hand, MHD modelling works have now matured to the point that a direct comparison to observations is conceivable. Indeed, 3D MHD numerical simulations of the star-disc interaction become possible (Romanova et al. 2008; Zanni et al. in prep.) as well as MHD numerical simulations of jet propagation reaching scales of 100 AU (Murphy et al. in prep). Therefore we have now the prospect to gather in the coming years a coherent vision of the accretion-ejection connexion in young stars.

This contribution would not have been possible without the fruitful collaborations generated by the JETSET network as well as the input/inspiration from many collaborators, especially: V. Agra-Amboage, S. Cabrit, J. Ferreira, M. Benisty, F. Bacciotti, T. Ray, M. Gudel, J.F. Donati, J. Pety.

References

Agra-Amboage, V., Dougados, C., Cabrit, S., Ferruit, P., Garcia, P. 2009, A&A, 493, 1029

Agra-Amboage, V. 2009, PhD thesis.

Bacciotti, F., Ray, T. P., Mundt, R., Eislöffel, J., & Solf, J. 2002, ApJ, 576, 222

Bessolaz, N., Zanni, C., Ferreira, J., Keppens, R., Bouvier, J. 2008, A&A, 478, 155

Blandford, R. D. & Payne, D. G. 1982, MNRAS, 199, 883

Cabrit, S., Pety, J., Pesenti, N., Dougados, C. 2006, A&A, 452, 897

Cabrit, S., Codella, C., Gueth, F., et al. 2007, A&A, 468, L29

Casse, F. & Ferreira, J. 2000, A&A, 361, 1178

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

Coffey, D., Bacciotti, F., Ray, T. P., Eislöffel, J., Woitas, J. 2007, ApJ, 663, 350

Combet, C., & Ferreira, J. 2008, A&A, 479, 481

Donati, J.F., et al. 2007, MNRAS, 380, 1297

Donati, J.F., et al. 2008, MNRAS, 386, 1234

Dougados, C., Cabrit, S., Lavalley, C., & Ménard, F. 2000, A&A, 357, L61

Ferreira, J. 1997, A&A, 319, 340

Ferreira, J., Dougados, C., Cabrit, S. 2006, A&A, 453, 785

Gudel, M., Telleschi, A., Audard, M., et al. 2007, A&A, 468, 515

Gudel, M., Skinner, S. L., Audard, M., Briggs, K. R., Cabrit, S. 2008, A&A, 478, 797

Hussain, G,. et al. 2009, MNRAS, 398, 189

Kraus, S., Hofmann, K.-H., Benisty, M., et al. 2008, A&A, 489, 1157

Lavalley-Fouquet, C., Cabrit, S., Dougados, C. 2000, A&A, 356, L41

Pety, J., Gueth, F., Guilloteau, S., Dutrey, A. 2006, A&A, 458, 841

Panoglou, D., et al. A&A in press A. C., 1996, ApJ, 468, L103

Ray, T., Dougados, C., Bacciotti, F., Eislffel, J., Chrysostomou, A. 2007, in Protostars and Planets V, B. Reipurth, D. Jewitt, and K. Keil (eds.), University of Arizona Press, Tucson, p.231-244

Romanova, M. M., Kulkarni, A. K., Lovelace, R.V.E. 2008, ApJ, 673, L171

Sauty, C. & Tsinganos, K. 1994, A&A, 287, 893

Sauty, C., Trussoni, E., Tsinganos, K. 2002, A&A, 389, 1068

Shu, F., Najita, J., Ostriker, E., et al. 1994, ApJ, 429, 781

Tatulli, E., et al. 2007, A&A, 464, 55

Terquem, C. 2003, MNRAS, 341, 1157

Zanni, C., Ferreira, J., Bessolaz, N., A&A, in press

Whelan, E. T., Ray, T. P., Bacciotti, F., et al. 2005, Nature, 435, 652

Whelan, E., T., et al. 2007, ApJ, 659, L45