Jets at all Scales
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Molecular and atomic jets in young low-mass stars: Properties and origin

Sylvie Cabrit[1] **and J. Ferreira**[2] **and C. Dougados**[2]

[1]LERMA, Observatoire de Paris, CNRS
61 Avenue de l'Observatoire, F-75014 Paris
email: `sylvie.cabrit@obspm.fr`

[2] LAOG, Observatoire de Grenoble, CNRS
email: `ferreira@obs.ujf-grenoble.fr, dougados@obs.ujf-grenoble.fr`

Abstract. The key characteristics of molecular and atomic ejection from young stars are summarized, with emphasis on similarities across evolutionary stages, and the need for efficient magnetic collimation and ejection extracting a large fraction of the accretion power. The jet kinematics, and its dust and molecular content, are confronted to steady MHD jet models, and the probable contribution of non-steady processes is pointed out.

Keywords. stars: pre–main-sequence; stars: winds, outflows; ISM: jets and outflows; ISM: molecules

1. Introduction

Bipolar ejection of matter in molecular and/or atomic form is a ubiquitous phenomenon in accreting young stars of all evolutionary phases (see Section 2). However, the ejection mechanism(s), and the region(s) that dominate the outflow mass-flux and power (stellar surface / magnetosphere / inner disk edge / extended disk surface) are still heavily debated and the subject of intense research (cf. Tsinganos *et al.* 2009 for recent views). One important clue is that the ejection/accretion efficiency and the jet collimation remain similar over decades in source age, requiring a highly efficient *magnetic* ejection and collimation process (see Sections 3,4). Additional constraints on the ejection mechanism are provided by the recent discovery of transverse velocity decrease, tentative rotation signatures, metal depletion, and molecules in jets (see Section 5). Among proposed *steady* MHD ejection models, disk winds seem more promising to explain these properties. However, there is mounting evidence that non-steady interaction between the disk and the stellar magnetosphere also contributes to the observed outflow features (see Section 6).

2. Ubiquity of jets in accreting young stars

Jets are observed in *all* classes of young stellar objects where accretion is occuring, although their strength and molecular fraction declines with age (see Cabrit 2002 for a detailed comparative description):

- In the youngest embedded protostars ("Class 0") of ages $\leqslant 10^4$ yr, where the infall rate is highest: outflow activity is most apparent in molecular tracers and takes two aspects, illustrated in Fig. 1: (1) slow, moderately collimated bipolar CO outflow cavities of swept-up ambient gas, moving at $V \leqslant 10$ km s^{-1}, and (2) fast, highly collimated molecular "jets" seen in SiO, CO, and H_2 at $V > 10-100$km s^{-1}, appearing as molecular "bullets" on larger scales > 0.1 pc (Bachiller & Tafalla 1999). The atomic counterpart

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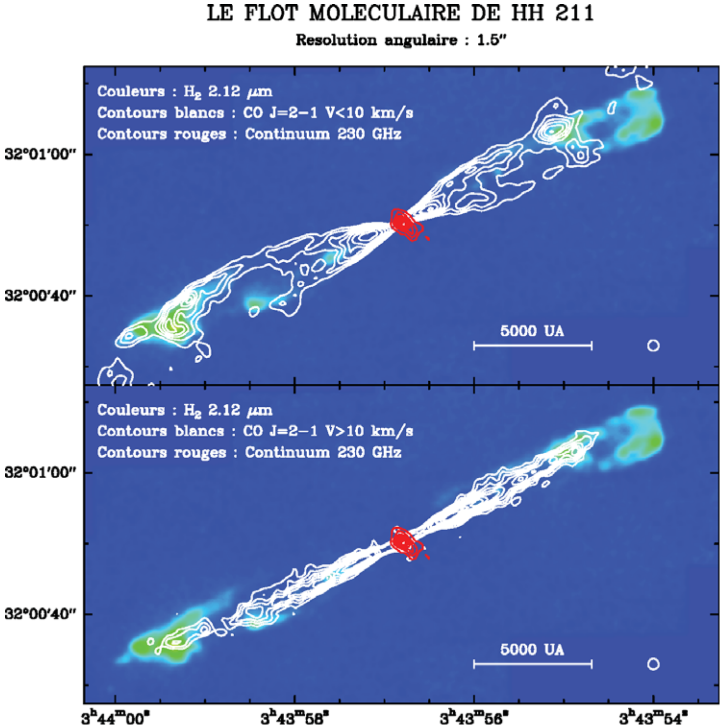

Figure 1. Bipolar ejection tracers in the young Class 0 protostar HH211; White contours of CO(2-1) emission (Gueth & Guilloteau 1999) delineate a swept-up bipolar cavity at low speed (top panel), and a narrow axial jet at high $V \geqslant 10$ km s^{-1} (bottom panel). The background image shows shock-excited H_2 in the leading jet bowshocks (Mc Caughrean *et al.* 1994).

appears to carry a lower mass-flux than the molecular jet (Dionatos *et al.* 2009, 2010). Only a handful of such jets have been mapped in detail so far, but the collimation and kinematics of outflow cavities appear consistent with jet-driven bowshocks in young low-luminosity Class 0 sources, while a wider-angle component is needed in massive / older flows (Cabrit, Raga, & Gueth 1997; Downes & Cabrit 2003; Arce *et al.* 2007 and refs. therein).

- In evolved infrared protostars ("Class I"), of age $\simeq 10^5$ yr, where residual infall is occuring at much slower rate: jets become brighter in optical ionic lines out to several pc (see top panel of Fig. 2, and Reipurth & Bally 2001 for a review) and H_2 carries a lower mass-flux than the atomic gas (Nisini *et al.* 2005, Podio *et al.* 2006). Swept-up CO outflows are weaker than in the Class 0 stage (Bontemps *et al.* 1996),
- In "Class II" pre-main sequence stars of age $\simeq 10^6$ yr, which have no more envelope but retain an active accretion disk: High-velocity atomic jets are much fainter, with the jet beam traced out to $\leqslant 500$ AU (Hartigan *et al.* 1995, Hirth *et al.* 1997). H_2 counterparts tend to be slower and less collimated than the jet (see bottom panel of Fig 2; Beck *et al.* 2008). An important finding is that jets are absent in young stars with no accretion disks (Hartigan *et al.* 1995). Hence, *accretion is clearly fundamental for the jet process.* In contrast, jets are seen over a wide range of stellar masses, from brown dwarfs up to $M_\star > 2M_\odot$ (see Whelan, this volume, Ray *et al.* 2007, Bacciotti 2009), indicating a robust universal mechanism.

A universal property of stellar jets at all stages is their "knotty" appearance, with very similar knot spacings in Class 0 and Class I (Cabrit 2002). These features trace internal

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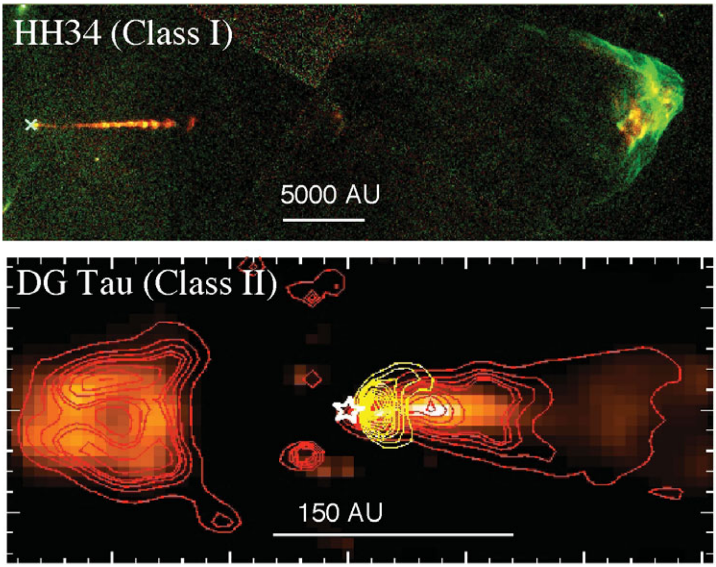

Figure 2. Bipolar ejection in late phases of accreting young stars: (i) top panel: evolved infrared Class I protostar (HH34), with jet image in [S II] and Hα (from Reipurth *et al.* 1997); the knotty structure arises from time variability; (ii) pre-main sequence Class II star (DG Tau): The colour image traces fast [Fe II] with $V > 150$ km s^{-1}, while red contours trace slower [Fe II] with $V \simeq 50 - 150$ km s^{-1}; yellow contours trace H$_2$ with $V < 20$ km s^{-1}. Note the wider opening angle at lower velocity, and the "bubble" features near the tip of both lobes (adapted from Agra-Amboage *et al.* 2010).

shocks driven by velocity variability on several timescales $\simeq$ 30–60 yrs, 300 yrs, and 1000 yrs, with longer modes having larger amplitudes (Raga *et al.* 2002). An even faster mode of period $\simeq$ 3–5 yrs is identified in Class II jets (Hartigan *et al.* 2007; Agra-Amboage *et al.* 2010). The origin of such variations is yet unclear, although jet wiggling suggests orbital motions of period 50 yrs in some sources (Anglada *et al.* 2007; Lee *et al.* 2010).

3. Jet power compared to the accretion power

While both accretion and ejection strongly decrease over time, they remain tightly correlated with one another:

- Estimates of the ejection power in the early Class 0 phase rely heavily on observations of the larger, slower swept-up CO cavities, for which a rich body of data is available. The momentum injection rate in swept-up Class 0 molecular outflows shows a clear correlation with the source bolometric luminosity over 5-6 orders of magnitude, probably tracing an underlying ejection-accretion correlation (see Fig. 3). The momentum efficiency is very high, $F_{\rm CO}c/L_{\rm bol} \simeq 1000(L_{\rm bol}/10L_{\odot})^{-0.3}$, and clearly rules out radiative or thermal ejection mechanisms (Lada 1985; Cabrit & Bertout 1992). Assuming that the outflows are momentum-driven by an underlying wind/jet of speed $V_w \simeq 200$ km s^{-1}, the inferred wind mechanical luminosity, $L_{\rm w} = 0.5\ F_{\rm w} V_w$, is 50%–100% of L$_{\rm bol}$ in low-luminosity sources, indicating that *the ejection mechanism extracts a considerable fraction of the accretion power* (Cabrit & Bertout 1992; Cabrit 2002). Direct measurements of the jet mass-flux in a few Class 0 sources confirm this result (Lee*et al.* 2010). The lower momentum efficiency $F_{\rm CO}c/L_{\rm bol} \simeq 10 - 100$ for L$_{\rm bol} \gtrsim 10^4 L_{\odot}$ could be due to the increasing contribution of the photospheric luminosity L$_\star$ in massive protostars. Indeed, reasonable assumptions about

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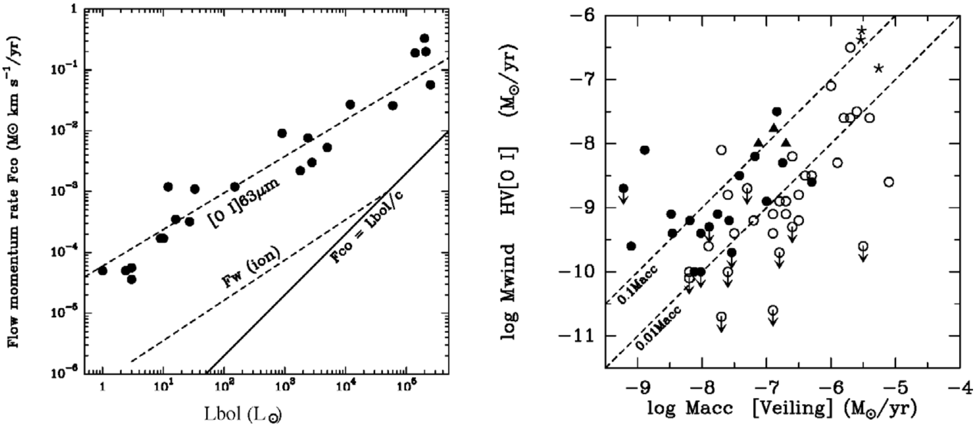

Figure 3. *Left:* Correlation between the momentum flux $F_{\rm CO}$ in the swept-up CO outflow and the source bolometric luminosity $L_{\rm bol}$ in Class 0 sources. The two dashed lines show the typical momentum flux in the ionized part of the jet (Fw(ion)) and in dissociative shocks ([OI]63μm). Adapted from Richer *et al.* (2000). *Right:* mass-loss rate in high-velocity atomic gas versus disk accretion rate in Class II stars. Open circles are from Hartigan *et al.* (1995), while filled circles use revised $\dot{M}_{\rm acc}$ from Muzerolle *et al.* (1998) and filled triangles use revised $\dot{M}_j$ from spatially resolved jet data. Star symbols denote Class I sources. From Cabrit (2007b).

the stellar mass or age suggest a roughly similar ratio $(\dot{M}_{\rm w}/\dot{M}_{\rm acc})(V_w/V_{K,*}) \simeq 0.1$-$0.3$ in Class 0 sources of all luminosities (Richer *et al.* 2000, Beuther *et al.* 2002).

- In Class II sources, statistical studies clearly indicate that ejection is correlated with accretion, not with $L_\star$ (Hartigan *et al.* 1995). Although uncertainties in jet mass-flux $\dot{M}_j$ and $\dot{M}_{\rm acc}$ for individual sources can reach a factor 3–10, the most reliable estimates to date yield average mass, momentum, and energy efficiencies (two-sided): $(2\dot{M}_j)/\dot{M}_{\rm acc} \simeq 0.1$-$0.2$, $(2F_j)c/L_{\rm acc} \simeq 100$–$300$, $(2L_j)/L_{\rm acc} \simeq 0.1$ (see Fig. 3; Cabrit 2007b; Bacciotti 2009). Similar values are obtained in Class I sources, from observations of CO swept-up cavities and atomic jets (Bontemps *et al.* 1996; Hartigan, Morse, & Raymond 1994; Antoniucci *et al.* 2008).

4. Jet collimation, and collimating agent

Measures of jet collimation have greatly progressed over the last decade, thanks to the sub-arcsecond resolution afforded by adaptive optics and the *Hubble Space Telescope* in atomic jets, and by radio interferometers in molecular jets.

Studies of nearby atomic Class II stars reveal that the jet axis is closely aligned with the disk axis at the base, even if jet wiggling is present further out (eg. Anglada *et al.* 2006). The apparent half-opening angle of the jet beam drops from $\simeq 10-15^o$ initially to 2–3^o beyond 50 AU, with a typical jet radius of 10 AU at this distance (see Hartigan *et al.* 2007; Ray *et al.* 2007 and references therein). Hence, the bright fast jet core appears to be collimated *on small, inner disk scales.*

Another striking result is that jet widths in Class 0 protostars, which possess a very dense infalling envelope, are similar to those in Class II stars, with no envelope and a thin disk (see Fig. 4, and Cabrit *et al.* 2007). Thus, jet collimation cannot rely on ambient thermal or ram pressure. Indeed, ambient densities around Class II stars seem too low by several orders of magnitude to provide jet collimation on the observed scale (see Cabrit

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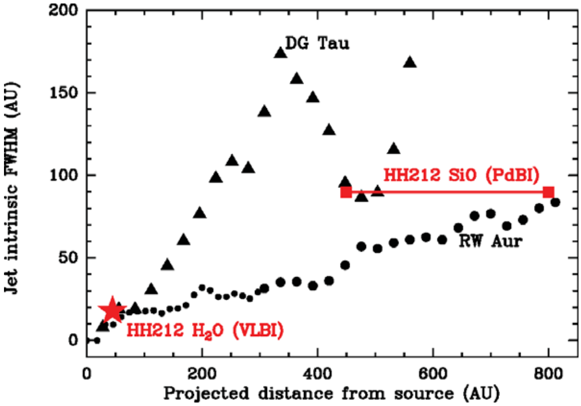

Figure 4. Width of the jet from the young Class 0 protostar HH 212 versus distance from the source, as observed in H_2O masers (red star; from Claussen *et al.* 1998) and in SiO (red bar). The similarity to jet widths in T Tauri stars with no circumstellar envelope (black symbols) favors a magnetic collimation process. From Cabrit *et al.* (2007).

2007a for a detailed discussion of this issue). A *magnetic* collimation process thus appears called for.

5. New constraints: Jet transverse kinematics and composition

5.1. *Transverse velocity decrease*

The flow speed appears to drop away from the jet axis. A wider-angle, slower “sheath” surrounding the fast axial jet is clearly seen in the DG Tau jet (see bottom panel of Fig. **??**; Lavalley-Fouquet *et al.* 2000; Bacciotti *et al.* 2000); A transverse velocity decrease is also detected in other Class II jets such as CW Tau or Th 28 (Coffey *et al.* 2007), and in the Class 0 jet HH 212 (Lee *et al.* 2008). Whether this slower “sheath” around the fast jet beam is intrinsic to the launch mechanism, or develops from interaction with ambient gas or internal shocks or instabilities, is yet unclear (Garcia-Lopez *et al.* 2008; Agra-Amboage *et al.* 2010). In any case, it appears challenging to ejection models that predict a *fast* wide-angle wind around the jet (see eg., Cai *et al.* 2008).

5.2. *Tentative jet rotation signatures*

Transverse velocity shifts of 5–10 km s^{-1} suggestive of jet rotation have been reported in DG Tau and several other Class II and Class I jets (see Bacciotti 2009 for a recent review). These data set important constraints on models where the jet traces a steady centrifugal MHD disk wind extracting most of the angular momentum from the accretion flow. The observed shifts imply an outer MHD launch radius $r_e \simeq 0.15$–3 AU for *atomic streamlines* and a magnetic lever arm parameter $\lambda = r_A^2/r_o^2 \simeq 4$–13 (see Bacciotti *et al.* 2002; Anderson *et al.* 2003; Pesenti *et al.* 2004; Ferreira *et al.* 2006). Such low values of λ predict moderate maximum flow speeds of $\simeq 200 - 500$ km s^{-1} and an ejection efficiency $\simeq 0.05$–0.1, in line with observations (Ferreira *et al.* 2006; Agra-Amboage *et al.* 2010). The r_e and λ values are in fact upper limits for MHD disk winds, since transverse shifts may include other effects than rotation, eg. jet precession, binary orbital motion, or shock asymmetries (eg. Cerqueira *et al.* 2006; Cabrit *et al.* 2006).

Tentative rotation has also been reported in two molecular Class 0 jets in Orion (Lee *et al.* 2007, 2008, 2009). However, the inferred small r_e values are highly uncertain,

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because the transverse velocity gradient occurs on scales $\simeq$ 2–3 times smaller than the beam size. Under such circumstances, any real rotation signature is expected to be *strongly beam-smeared*, so r_e would be underestimated (Pesenti *et al.* 2004; see Cabrit 2009 for a detailed discussion). The closer-by and better resolved CO jet from CB26 shows a clear pattern suggestive of rotation (Launhardt *et al.* 2009). The inferred launch radius is 30 AU if angular momentum is conserved, and 0.5–5 AU for a steady centrifugal MHD wind (Cabrit 2009). But it is intringuing that the similar CO jet from HH30 does not show any clear rotation signature (Pety *et al.* 2006). The enhanced resolution brought by the ALMA interferometer will be critical to progress on this topic.

5.3. *Metal depletion in jets*

The gas phase depletion of refractory species such as Fe, Si, C, Ni, Ca, has been measured in several Class 0 and Class I jets by comparing their emission line fluxes with other species that do not significantly deplete into grains, such as hydrogen, sulfur, phosphorus, and oxygen (Nisini *et al.* 2002, 2005; Podio *et al.* 2006, 2009; Dionatos *et al.* 2009, 2010). Typical gas-phase depletions of 20%-90% with respect to solar abundances are inferred, with a trend for stronger depletion closer to the source. Similar iron depletion levels are suggested in the inner 150 AU of the Class II jet from DG Tau, with higher depletion at lower speed (Agra-Amboage *et al.* 2010). These data suggest that the bulk of the emitting jet material does not originate from the star, but from a more external region where 20–90% of the dust grains can survive, with slower gas ejected from more dusty regions.

5.4. *Molecules in jets*

The presence of molecules in jets at speeds $\geqslant$ 100km s^{-1} well exceeding the typical dissociative shock limit in the ISM of $\simeq$ 25-35 km s^{-1}, has been a challenge since its discovery. Entrainment of ambient molecules by an underlying atomic jet does not appear efficient enough to produce the observed H_2 and CO columns, as any turbulent entrainment layer should be very thin (Taylor & Raga 1995), and there is little ambient material left to sweep-up behind the leading bowshock. Synthesis of molecules in a dust-free stellar wind can be efficient for CO and SiO, but excessive high mass-fluxes $> 10^{-5}$ $M_{\odot}\mathrm{yr}^{-1}$ appear to be required to reach substantial H_2 abundances (Ruden *et al.* 1990). H_2 reformation behind dust-free shocks is efficient only at low shock speeds $<$ 15 km s^{-1} (Raga *et al.* 2005).

Alternatives avoiding these caveats would be that H_2 reforms in a dusty jet (Garcia-Lopez *et al.* 2008) or that molecules are gently magnetically accelerated from the disk surface. We have recently performed detailed calculations of the chemical and thermal structure in an MHD disk wind with $\lambda \simeq 13$ and launch radii $\simeq$ 0.2-10 AU, including heating by ambipolar diffusion, and ionization and dissociation by coronal X-rays and UV radiation from the accretion shock (Panoglou *et al.* 2010). As shown in Fig. 5, we find that (1) adiabatic and H_2 cooling can efficiently limit the gas heating and collisional dissociation, yielding asymptotic temperatures $\simeq$ 700 K in Class 0 to 2500 K in Class I, II in agreement with observations (Dionatos *et al.* 2010; Beck *et al.* 2008); (2) H_2 is more efficiently screened against photo-dissociating UV at high mass accretion rate. This would explain the trend for a higher molecular fraction in Class 0 jets compared to Class I, II. The chemical effect of internal shocks propagating in such disk winds, in particular the release of SiO from grains, should now be investigated to compare against observed jet chemistry (Cabrit *et al.* 2007; Tafalla *et al.* 2010).

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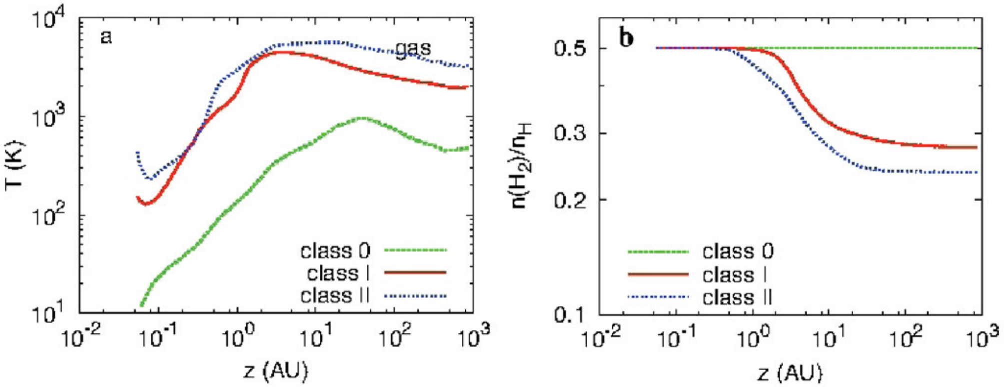

Figure 5. *Left*: Predicted gas temperature along an MHD disk wind streamline launched from 1 AU, for an accretion rate of 5×10^{-6} $M_{\odot}\mathrm{yr}^{-1}$(Class 0), 10^{-6} $M_{\odot}\mathrm{yr}^{-1}$(Class I), and 10^{-7} $M_{\odot}\mathrm{yr}^{-1}$(Class II). Ambipolar diffusion heating is eventually balanced by H_2 cooling, with a lower asymptotic temperature at higher accretion rate. *Right:* H_2 abundance relative to H nuclei on MHD disk wind streamlines launched from 1 AU. Abundance increases with accretion rate, as the denser flow is better self-screened against stellar UV photons. From Panoglou *et al.* (2010).

6. Conclusions

The high ratio of jet to accretion power in young low-mass stars (10% in disk-dominated sources, and $\geqslant 50\%$ in protostars) suggests that jets are extracting a large fraction of the accreting angular momentum down to a few stellar radii. Magnetic fields clearly play an important role in this process, as indicated by the tight jet collimation operating within 50 AU. The similarity in $\dot{M}_{\rm w}/\dot{M}_{\rm acc}$ among all evolutionary stages and masses suggests that a universal ejection mechanism might be at work.

However, the growing set of observational constraints are very challenging to most currently proposed *steady* MHD ejection models (see Cabrit 2009 for a detailed discussion): Wave-driven *stellar winds* may have difficulties in explaining the high ejection/accretion ratio $\simeq 0.1$ (Cranmer 2009, Ferreira *et al.* 2006), and the depletion of refractory elements. The magneto-centrifugally driven *"X-wind" model* from the inner disk edge (Cai *et al.* 1998) predicts a fast wide-angle wind that is not seen. Magneto-centrifugal disk winds from an extended disk region may explain the drop in velocity away from the jet axis and the rotation signatures (Pesenti *et al.* 2004); apparent jet widths (Ray *et al.* 2007; Stute *et al.* 2010), presence of molecules in jets (Panoglou *et al.* 2010), and ejection/accretion ratio (Ferreira *et al.* 2006). However, the small magnetic lever arms $\lambda \leqslant 4-13$ compatible with constraints on jet rotation require strong heating within the disk (Casse & Ferreira 2000), of yet unclear origin.

Another challenge to steady disk winds is the recent evidence for velocity variability on a timescale of $\simeq$ 3–10 yrs in Class II jets (Hartigan *et al.* 2007; Agra-Amboage *et al.* 2010). This is 500 times the orbital period at the inner disk edge but close to the orbital period at 1–3 AU, hence any extended disk wind would not be steady in its outer regions. Also intriguing is the observation in XZ and DG Tau of episodic inflating "bubbles" (Krist *et al.* 2008; Bacciotti *et al.* 2000; Agra-Amboage *et al.* 2010; see Fig. 2,bottom), reminiscent of laboratory experiments of episodic "magnetic towers" driven by a strong B_{ϕ} pressure gradient (Ciardi *et al.* 2009). Such variable features are probably related to the non-steady interaction between the disk and the twisted stellar magnetosphere, a process which is necessarily present, and crucial to spin down the accreting star (Ferreira *et al.* 2006, Zanni 2009, Fendt 2009; Romanova 2009; Fendt *et al.*, this volume). The

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relative contribution of unsteady/steady ejections to the total jet power and mass-flux remains to be established.

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Discussion

DE GOUVEIA DAL PINO: The steady-state models with implicit chemistry you showed to explain molecular jets are kind of ideal because actually if we include intermittency then we have shocks and knots and then the shocks may destroy the molecules: so, I don't think a steady-state model may solve this question on molecular jets survival. Could you comment on this ?

CABRIT: Indeed, you are completely right that internal shocks might modify the chemical abundances, possibly dissociating molecules and/or reforming them in dense and cool postshock layers. Hence, shocks should be included in any model aiming at reproducing the jet composition. However, the effect of shocks on chemistry depends critically on whether the shocks are discontinuous (J-type) or continuous (C-type). This in turn depends on the (unknown) preshock H_2 content, ionization fraction, and transverse magnetic field in the jet. Our steady-state chemistry calculations are thus a required first step in that they provide these initial pre-shock conditions in the case of MHD disk winds. Using these conditions, we find that internal shocks in class 0 disk winds should develop a magnetic precursor (C-type) and be much less dissociative than under ISM conditions. The predicted H_2 spectrum is in excellent agreement with *Spitzer* observations of class 0 jets (V. Taquet, in prep.). Other molecules, eg. SiO, could in principle be formed in such shocks.

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