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Modeling the magnetized accretion and outflows in young stellar objects

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Abstract. Recent results of magnetohydrodynamic (MHD) simulations are presented treating the launching of jets from young stellar object accretion disks. The simulations consider the evolution of magnetically diffusive disks that eject high-speed outflows. A few exemplary results are presented: (i) the disk structural evolution that leads to different launching conditions over time, (ii) a general interrelation between the disk magnetization at the outflow launching radius and the outflow asymptotic properties, (iii) jet launching within a self-generated disk magnetic field amplified by a disk mean field dynamo, and (iv) simulations of jets from orbiting jet sources.

Key words: accretion, accretion disks – magnetohydrodynamics (MHD) – ISM: jets and outflows – stars: mass loss – stars: pre-main sequence

1. Introduction

Jets are powerful signatures of astrophysical activity and can be observed over a wide range of energy output and spatial extent. Among other jet sources - mainly relativistic sources such as active galactic nuclei - young stellar objects are particularly interesting, as they allow to observe certain dynamical properties that are essential for modeling. For relativistic jets, mainly observed in synchrotron radio emission, we do not know their exact velocities or mass fluxes.

For protostellar outflows, outflow mass fluxes were found that are proportional to the accretion rate, suggesting a physical link between accretion and ejection (e.g. Edwards et al., 2006). Observations also indicate the existence of a strong magnetic field in the regions where jets are formed (Carrasco-González et al., 2010), and for the jet-launching source (e.g. Edwards et al., 1994).

To summarize, the following observationally confirmed features are essential for our understanding of jet formation and are therefore important ingredients for any theoretical modeling of disks and jets. These are (i) the existence of an *accretion disk* in jet sources, and estimates of the accretion rates, (ii) the existence of a strong *magnetic field* in jets and jet sources, and (iii) jet *knots* that are believed to be shocked gas, from which essential dynamical parameters such as jet *velocity* and *density* can be derived.

It is commonly accepted that MHD processes are essential for launching, acceleration and collimation of outflows from accretion disks (Blandford & Payne, 1982; Pudritz & Norman, 1983; Pudritz et al., 2007).

Considering the topic of this conference, jets from young stars indeed require the existence of a considerably *stable magnetic field* over the jet life time. However, the observations of jet knots (however being generated) also indicate some *time-dependent* variation of the field structure.

2. Jet launching - from accretion to ejection

We distinguish between *jet launching* - the transition from accretion to ejection - and *jet formation* standing for the acceleration and collimation process of a disk wind into a narrow jet. Jet *formation* is usually understood as due to the magneto-centrifugal slingshot mechanism. Outflows of lower velocity are built up as so-called tower jets accelerated by the magnetic pressure gradient of the toroidal field. Jet *launching* is more difficult to treat as interrelating the disk physics with the jet physics. Both differ in several aspects, in particular concerning their time scales. For example, disks are viscous and magnetically diffusive, while jets and outflows can be treated in ideal MHD. Further, disks may have a turbulent, strongly tangled field component, while fast jets rely on the existence of a smooth, large-scale magnetic field.

3. Basic physical processes

The outflow launching is not yet fully understood in all detail. However both, analytical modeling (Li, 1995; Ferreira, 1997) and numerical simulations (Casse & Keppens, 2002; Kuwabara et al., 2005; Zanni et al., 2007) agree on the main launching mechanisms involved. The general idea is visualized in Fig. 1: gas is advected along the disk. A large-scale magnetic field penetrates the disk. The magnetic flux distribution is affected by advection and diffusion of the field through the disk. The launching conditions vary along the disk and in time.

Disk material can be accreted across the magnetic field as the disk plasma is magnetically diffusive. In other words, the existence of magnetic diffusivity is essential in order to allow the material to be exchanged between magnetic flux surfaces. The magnetic diffusivity η is believed to be of turbulent origin. Figure 1 shows how the streamlines cross the magnetic field lines, and how they connect different field lines in disk and outflow.

The very launching process, the lifting of disk material into the outflow is a magnetic process (Ferreira, 1997; Ferreira et al., 2006), where Lorentz forces $\boldsymbol{F}_{\rm L} \propto \boldsymbol{j} \times \boldsymbol{B}$ play a leading role. If the vertical Lorentz force decreases vertically, gas pressure gradients may lift the material. The toroidal Lorentz force accelerates the plasma azimuthally, leading to a radial centrifugal acceleration.

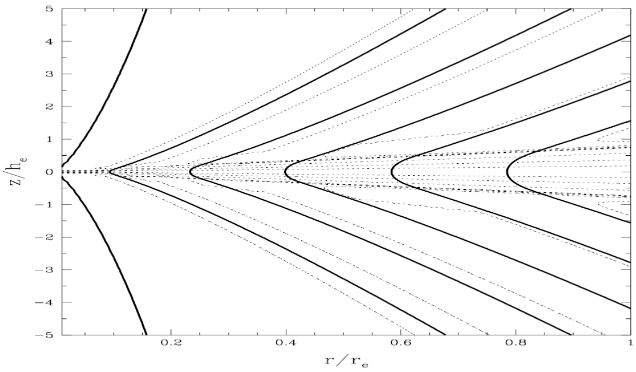

Figure 1. Streamlines of gas (dashed) and magnetic field lines (solid) of a self-similar accretion-ejection solution (taken from Ferreira, 1997).

Modeling the launching process means figuring out (either analytically by numerical simulations) certain magnetic field configurations that provide favorable Lorentz forces for launching and acceleration.

Once lifted above the disk surface, the further acceleration is by the magneto-centrifugal effect (Blandford & Payne, 1982; Pudritz & Norman, 1983) in case of strong poloidal magnetic fields, or by the vertical magnetic pressure (tower jets; Lynden-Bell, 1996) in case of low magnetic flux. The collimation into a narrow beam is accomplished by the pinching forces of the toroidal magnetic field B_ϕ. Simulations of the acceleration and collimation processes of jets forming from the disk surface have been performed in great detail by a number of authors (see e.g. Ustyugova et al., 1995; Ouyed & Pudritz, 1997; Romanova et al., 1997).

Note that while the magnetic field is essentially driving the jet, its role is merely to convert potential energy from disk material into kinetic outflow energy.

4. Simulations of jet launching

Here we present example results of recent jet launching simulations. In general, Fig. 2 shows the evolution of the inner part of a jet launching accretion disk. The magnetic field first diffuses outwards (shown are flux surfaces $\Psi \propto \int B_z dr$), until accretion begins and leads to advection of flux. Obviously, the launching conditions change over time.

4.1. Jet launching and disk magnetization

We applied a novel approach to the jet-launching problem to obtain correlations between the physical properties of the jet and the underlying disk. We have investigated a wide parameter range of disk magnetization $\mu_{\rm D}(r_0) =$

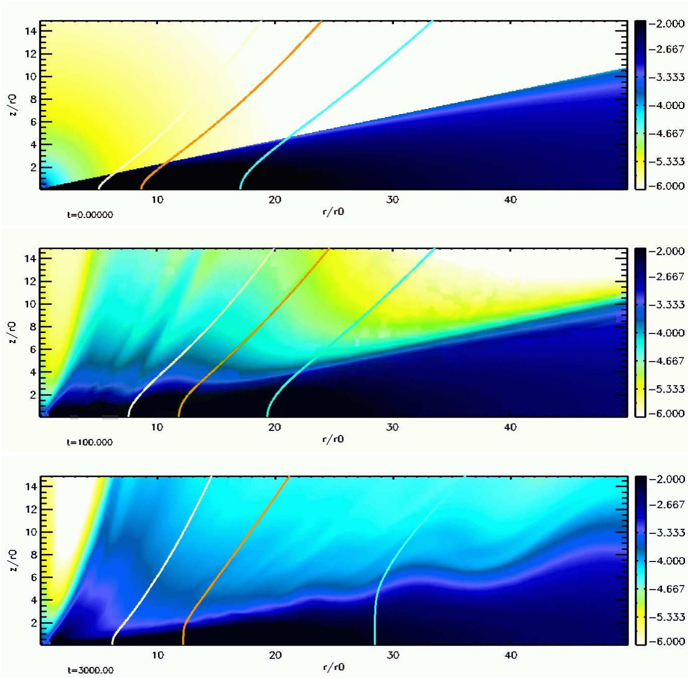

Figure 2. Advection and diffusion of outflow-launching magnetic flux surfaces. Three flux surfaces are shown (disk density in color). The panels show the inner part (length scale normalized to inner disk radii) of a simulation reaching $r = 100$, $z = 300$ in extend (Sheikhnezami et al., 2012).

$10^{-3.5}...10^{-0.7}$ at the outflow launching point r_0. The magnetization μ measures the ratio of magnetic pressure to gas pressure. This study is complementary to the works of Tzeferacos et al. (2009) and Murphy et al. (2010) who investigated the jet launching along a disk surface with decreasing $\mu_{\rm D}(r)$.

As our main result, we have disentangled the disk magnetization at the outflow origin as the main parameter governing the outflow properties. Strongly magnetized disks launch more energetic and faster jets and, due to a larger Alfvén lever arm, these jets extract more angular momentum from the disk. These kinds of systems have, however, a weaker mass loading and a lower mass ejection-accretion ratio. Jets are launched at the disk surface where the magnetization is $\mu(r, z) \simeq 0.1$.

As an example, Fig. 3 shows the tight correlations between the total jet energy e and the mass loading k with the disk magnetization $\mu_{\rm D}$, respectively. The mass loading parameter k measures the amount of matter ejected per unit magnetic flux. Each differently colored line corresponds to a simulation with a

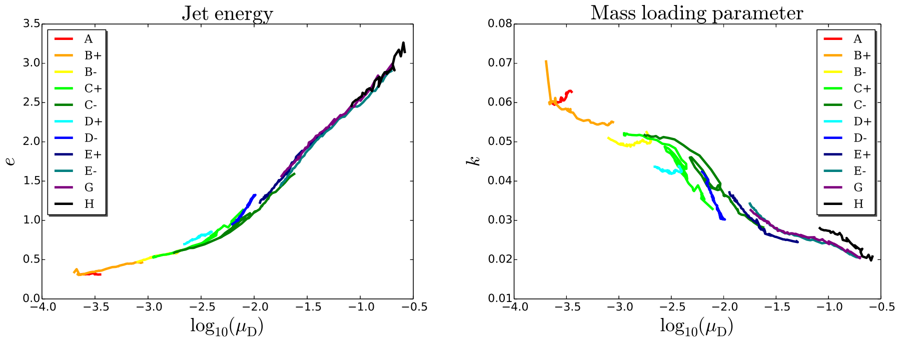

Figure 3. Jet properties with respect to the disk magnetization $\mu_{\rm D}$. The jet energy e, and the mass loading parameter k are shown. Each colored line represents the evolution of a single simulation up to 10,000 time units. Taken from Stepanovs & Fendt (2016).

different initial disk magnetization.

We also find indication of a critical disk magnetization $\mu_D \simeq 0.01$ separating the regimes of magneto-centrifugally driven and magnetic pressure-driven jets (indicated by the change in slope in Fig. 3). The existence of these two regimes has been discussed by Ferreira (1997), however, we obtain these correlations from simulations that include the dynamical evolution of disk and jet.

4.2. Launching by a disk-dynamo generated magnetic field

Most simulations of jet launching have been set up prescribing a large-scale initial magnetic flux. Exceptions are e.g. Bardou et al. (2001) or von Rekowski et al. (2003) considering a disk dynamo or a stellar dynamo that generate the jet driving magnetic field.

More recently we have presented MHD simulations exploring the launching, acceleration, and collimation of jets and disk winds considering the generation of the magnetic field by an α^2-Ω mean-field disk dynamo (Stepanovs et al., 2014). We found a dynamo-generated magnetic field of the inner disk similar to the commonly prescribed open field structure, favoring magneto-centrifugal launching. The outer disk field is highly inclined and predominantly radial. Here, differential rotation induces a strong toroidal field. Outflows from the outer disk are slower, denser, and less collimated.

We have further applied a toy model triggering a time-dependent mean-field dynamo. When the dynamo is suppressed as the magnetization falls below a critical value, the generation of the outflows and also accretion is inhibited.

Figure 4 shows snapshots of our simulation applying a time-dependent dynamo model. We display the density and velocity structure overlaid with magnetic field lines. Dynamo-active times follow dynamo-inactive times with periods

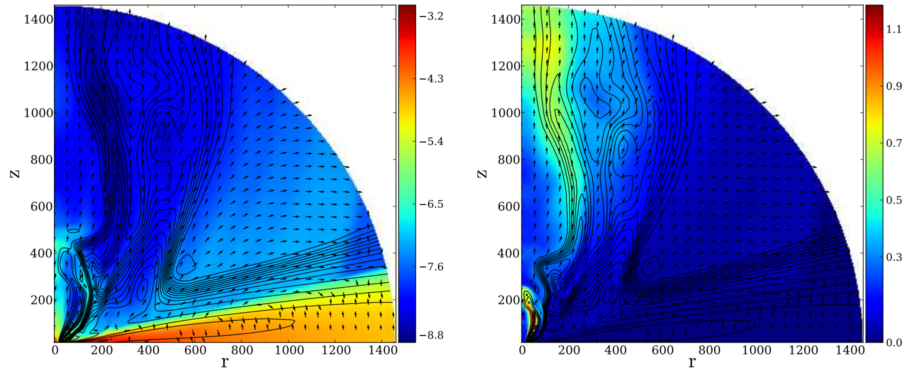

Figure 4. Jet launching from dynamo-active disks. Shown is the density (left) and outflow velocity (right) in code units (colors). The velocity is normalized to the Keplerian velocity at the inner disk radius, The dynamo model is time dependent with a period of about 100 orbital times. Superimposed are poloidal magnetic field lines (black), see also Stepanovs et al. 2014.

of about 100 disk rotations. During dynamo-active time periods new jet ejections happen close to the inner disk. In the figure two ejections periods are visible in the jet flow (more in velocity than in density), the latest one having reached $z = 200\, R_{\rm in}$, the earlier one currently at $z = 1200\, R_{\rm in}$.

4.3. 3D-launching simulations

Extending the launching setup to 3D, we have recently presented the first ever 3D simulations of the MHD accretion-ejection structure (Sheikhnezami & Fendt, 2015). We have implemented a 3D gravitational potential due to a companion star and run a variety of simulations with different binary separation. The simulations show typical 3D deviations from axial symmetry, such as jet bending outside the Roche lobe or spiral arms forming in the accretion disk. An exemplary parameter setup with a small binary separation of only $\simeq 200$ inner disk radii indicates the onset of jet precession - caused by the wobbling of the jet-launching disk. A final prove for precession can only be given by much longer simulations lasting several orbital time scales. In Fig. 5 we see the disk-realignment over time from the initial orientation towards the orbital plane. The secondary is located at $x = 200$ and $z = 60$ (outside the numerical grid).

5. Summary and outlook

So far we have discussed *global* models of jets launching in which the “microphysics” of the disk is approximated by averaged quantities such as (mean)

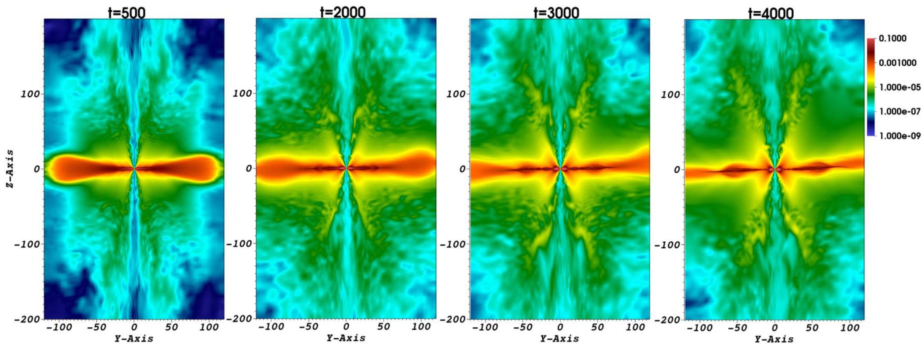

Figure 5. 3D jet launching from jet sources in binary systems. Shown is a time sequence of slices through the 3D simulation for the density structure. Taken from Sheikhnezami & Fendt (2015).

magnetic flux, plasma density, flow energy or angular momentum, and, in particular, mean turbulent diffusivity or a mean-field turbulent dynamo. This seems feasible and has so far provided promising results that are in nice agreement with analytical theory.

However, certain physical aspects that may play a role in reality have not yet been addressed in detail in global numerical launching models. Some are, however, currently investigated in (local and global) accretion disk simulations and will impact the future development of disk-jet launching modeling. Examples are e.g. (i) heating and cooling of the disk, (ii) a self-consistent description of the turbulent magnetic diffusivity, and similarly (iii) for the mean-field turbulent dynamo, then (iv) non-ideal MHD effects like ambipolar diffusion or Hall MHD, and the influence of (v) the stellar magnetic field, or (vi) the influence of radiation pressure.

While the main launching mechanism seems to be well understood from global launching simulations, a yet further, full understanding of jet launching will require a more complete understanding of the internal disk evolution that will require a high resolution and will be computed in a localized disk area.

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