Formation and propagation of MHD jets - relativistic jets, radiation pressure, and shock-induced rotation

Christian Fendt, Oliver Porth\textsuperscript{1}, and Bhargav Vaidya\textsuperscript{2}
Max Planck Institute for Astronomy, Königstuhl 17, D-69117 Heidelberg, Germany
E-mail: fendt@mpia.de

Abstract. We present recent results of magnetohydrodynamic (MHD) simulations of jet formation and propagation, discussing a variety of astrophysical setups. In the first approach the role of the disk magnetic flux profile and disk mass flux profile concerning the jet collimation degree is investigated. Our results suggest (and quantify) that in general magnetized outflows launched from a compact region close to the inner disk radius tend to be less collimated. The second setup considers simulation of relativistic MHD jet formation, considering jet launched from the surface of a Keplerian disks, demonstrating - for the first time - the self-collimating ability of relativistic MHD jets. We obtain Lorentz factors up to $\approx 10$ while acquiring a high degree of collimation of about 1 degree. We then present MHD jet formation simulations taking into account radiation pressure of a central luminous source. We investigate radiative effects on jet collimation and propagation - an environment which is interesting for outflows from massive young stars and active galactic nuclei. Finally, we present a model which explains a possible jet rotation by shock compression of an intrinsic helical magnetic field.

1. Introduction

Astrophysical jets are highly collimated beams of high-velocity material, observed in a variety of astronomical sources - among them young stellar objects (YSO), micro-quasars, or active galactic nuclei (AGN). The current understanding of jet formation is that these outflows are launched by magnetohydrodynamic (MHD) processes in the close vicinity of the central object - an accretion disk surrounding a protostar or a compact object \cite{1,2,3}. Besides the contribution of the disk wind to the overall jet flow, there will be a further contribution launched by the central object. In case of stellar sources, a stellar wind may contribute additional Poynting flux or pressure \cite{4,5,6}. In case of a central black hole, a central Poynting dominated spine jet may exist being driven by the Blandford-Znajek mechanism \cite{7}. The details of all the physical processes involved are, however, not completely understood.

In this proceedings we present results of axisymmetric MHD simulations investigating certain aspects of jet formation and propagation. As the structure and the evolution of the accretion disk as well as the origin and the distribution of the jet-launching magnetic field is not really known, we performed a parameter study exploring how the disk magnetic flux distribution and the disk wind density profile affect the asymptotic collimation degree (Sect. 2). In Sect. 3 we present simulations of collimating disk winds into relativistic jets applying (special)
relativistic MHD simulations from the surface of a disk which is in Keplerian equilibrium with a central compact object. Essentially, these results prove (for the first time) the self-collimating feasibility of relativistic MHD jets.

Jets may originate in a hot and luminous environment and may be subject to de-collimating radiation pressure. This is the topic of Sect. 4.

Jet rotation is observationally indicated for stellar jets. However, rotation is a natural ingredient for any jet launching. In Sect. 5 we argue that jet rotation can be induced also from jet-internal shocks which compress the helical field and give rise to a toroidal Lorentz force.

2. Jet collimation and the accretion disk magnetic flux profile

Here we show results of axisymmetric jet formation simulations from disks of different magnetic flux profile (see [8]). The physical grid size corresponds to \((r \times z) = (150 \times 300) \, r_{\text{in}}\), where \(r_{\text{in}}\) is the inner disk radius which could be properly scaled to the astrophysical object investigated.

Here we have applied the ZEUS-3D code.

We start from an initially force-free magnetic field distribution within a gas in hydrostatic equilibrium. The simulations evolve under the boundary condition of a prescribed mass flux launched from the disk surface into the outflow. We have run models covering a wide range of different profiles for the disk magnetic flux or the disk wind mass flux, both parameterized by power laws, \(B_{p,\text{disk}}(r) \sim r^{-\mu}\), and \(\rho_{\text{wind}}(r) \sim r^{-\mu_{\rho}}\). Both quantities can be combined in the disk wind magnetization parameter (similar to the Michel magnetization parameter [9]),

\[
\sigma_{\text{wind}} \sim B_{p,\text{disk}}^2 r^3 \Omega^2 / M_{\text{wind}} \sim r^{\mu_{\rho}}.
\]

We quantify the collimation degree by comparing the axial and lateral mass fluxes (see [8], [10]). Figure 1 shows the collimation degree \(\zeta \sim (\dot{M}_z / \dot{M}_r)\) plotted against the power law exponent of the disk wind magnetization \(\mu_{\sigma}\). Our main result is that steep magnetization profiles, resp. disk magnetic field profiles, are unlikely to launch highly collimated outflows. However, flat profiles - in general leading to a higher collimation degree - tend to be unstable, i.e. they do not evolve into a steady state.

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**Figure 1.** Outflow collimation degree as function of the power law index of the disk magnetic field, resp. magnetization profile. Error bars indicate flows which have not reached a steady state.
Figure 2. Logarithmic (rest-frame) density of the jet in the steady-state. Shown are poloidal magnetic field lines (solid white), electric current flow lines (solid black), characteristic MHD surfaces (dark grey dotted, dashed, solid), surface of escape velocity (grey dotted), light surface (light grey solid). The arrows in the top plot indicate the velocity field. The right figure is the enlarged central region. Note the location of the light surface $R_L(r, z) \equiv c/\Omega$, with the so-called angular velocity of the field lines $\Omega$. (Adapted from [12]).

3. Relativistic MHD jets from accretion disks

We have extended our non-relativistic simulations to the (special) relativistic regime using the PLUTO code [11]. In order to apply an astrophysically motivated Keplerian disk boundary condition for the jet outflow we have added Newtonian gravity to the special relativistic equations (see [12, 13]).

The standard setup involves a poloidal field strength considering a plasma-beta between 0.001 and 1 at the inner disk radius and a poloidal field profile which is fixed in time by the boundary condition. The toroidal magnetic field induced during the flow evolution is floated into the boundary domain. However, in an alternative approach we prescribe a higher Poynting flux by injecting plasma with a higher toroidal field strength (up to a factor 8). Depending on the Poynting flux injected, the resulting Lorentz factors of the jet reach number values between $\Gamma = 1.5 - 10$.

Typical jet opening angles for the relativistic part of the outflow are 1–7 degrees, however, on the physical scales covered by the simulations of up to 6000 Schwarzschild radii the asymptotic jet is not fully accelerated or collimated.

Figure 2 shows a typical result of a (mildly) relativistic jet with a Lorentz factor of 1.5. The
location of the magnetosonic surfaces is shown as also the location of the light surface where the hypothetical rotation of the field lines supercedes the speed of light, $R_L(r, z) \equiv c/\Omega$. The asymptotic region of the relativistic jet enclosed by the light surface is the truly relativistic part of the outflow. This part of the outflow originated close to the inner edge of the accretion disk deep in the potential well where the rotation is most rapid.

Having derived a physically consistent distribution of the magnetohydrodynamic variables by our numerical simulations - i.e. the jet magnetic field distribution, the density distribution, and the jet velocity - we may use this information to derive consistent radio synchrotron maps following a relativistic polarized radiation transfer within the jet (Fig. 3). Since particle acceleration is not included in the MHD model, additional assumptions have to be made. We have tested three tracers for the power-law particle acceleration, i.e. density, thermal pressure, or magnetic energy density [12, 13]. All tracers give a similar polarization structure, although the intensity distribution differs. The spiky axial structure results from a high temperature, thin axial outflow from the compact object area and could be considered either as a Blandford-Znajek jet or a coronal wind.

4. De-collimation of MHD jets by radiation pressure

Jets may be launched in a hot and luminous environment - examples are accretion disks around compact objects or massive young stars. In this case the outflow dynamics can be affected by the strong radiation field. In order to quantify this effect numerically, we have run simulations of MHD jet formation using the PLUTO code [11] and where we have implemented the physical effect of radiation pressure. Our model setup so far was applied for a central luminous star.
surrounded by an (also luminous) accretion disk [14]. Thus, both the central object and the surrounding inner hot accretion disk may contribute to the radiative forces. The model could be extrapolated to AGN jets, however, certain constraints on the parameter values must be carefully considered (e.g. the ionization degree, the temperature, the existence of lines).

The radiative force considered in our study

\[ \vec{F}_{\text{rad}} = \vec{f}_{\text{cont},*} + \vec{f}_{\text{cont},\text{disk}} + \vec{f}_{\text{line},*} + \vec{f}_{\text{line},\text{disk}} \]  

comprises of acceleration due to continuum radiation from the central object, \( \vec{f}_{\text{cont},*} \), and the disk, \( \vec{f}_{\text{cont},\text{disk}} \), and those due to lines forces from the disk, \( \vec{f}_{\text{line},\text{disk}} \), and the central object \( \vec{f}_{\text{line},*} \).

For the line forces we apply the well known CAK theory [15], which has been also explored for AGN disk winds by [16]. The line force is expressed as a product of the force due to continuum radiation and a force multiplier \( M(t) \). The optical depth parameter \( t \) is related to the velocity gradient along the l.o.s., the wind density, and the ion thermal speed \( v_{\text{th}} \), thus \( t = (\rho \sigma_{\text{e}} v_{\text{th}})/|\vec{n} \cdot \nabla (\vec{n} \cdot \vec{v})| \). An empirical form for \( M(t) \) as a sum over all lines for model atmospheres for massive OB stars has been defined as \( M(t) \sim kt^{-\alpha} \), where \( k \) and \( \alpha \) are line force parameters [17]. Depending on the selection of lines, typical values for \( k \) range from 0.4-0.6 and for \( \alpha \) between 0.3-0.7. A force multiplier parameterization, independent of arbitrary \( v_{\text{th}} \), was introduced by [18].

We start off with a pure MHD simulation similar to [19] or [8]. When a steady outflow is established after about 200 inner orbital periods, we switch-on the radiative forces. The radiative forces disturb the pure MHD jet structure, and a new quasi-steady state is reached after another 200 rotations [14].

Our results are the following (see Fig.4 for a visual summary of these results). The line-driven force from a central object can significantly modify the outflow dynamics in terms of collimation and acceleration. We find that the outflow velocity is increased by a factor of 1.5-2 by radiation forces as compared to the pure MHD flow. Also, the degree of collimation is visibly lowered, e.g., in a 30% change in the magnetic flux profile, thus a wider opening angle of the magnetic field lines. For the example of massive young stars we have investigated different stellar masses thus central luminosity and radiation pressure. We determine the amount of de-collimation by

\[ \text{Figure 4. MHD jet formation under radiation pressure. Example of outflows from massive young stars (taken from [14]). Comparison of opening angles for the field line with varying magnetic field strength (left): } B = 5.1 \text{ G (solid), 6.6 G (dashed) and 11.5 G (dotted). Jet opening angles (middle) at the Alfvén point (stars) and the fast point (bullets) of a field line rooted at } r = 5 \text{ AU for runs with different stellar mass and thus luminosity. Jet opening angles (right) for runs with different } \alpha \text{ (top panel), and different injection density } \rho_0. \]
Figure 5. Axisymmetric MHD simulation considering a high (external) Mach number jet propagation with a rather weak magnetic field (taken from [20]. Shown are the density distribution (top left), the radial velocity distribution (lower left), the negative (top) and positive (bottom) toroidal specific Lorentz force components (middle), and negative (top) and positive (bottom) toroidal velocity components (right) at dynamical time $t = 50$ for a sub-grid of $r < 4.0$ of the whole computational domain ($0.0 < r < 10.0, 0.0 < z < 30.0$), where $r = 1$ is the radius of the jet injected into the ambient gas.
measuring the opening angles of a typical magnetic field line at the magnetosonic points. We find that by increasing the central mass (thus luminosity) from e.g. $20 - 60 M_\odot$, the outflow opening angle changes from $20 - 32$ degree, indicating a substantial amount of jet de-collimation.

We have carried out simulations with different field strengths considering a plasma-β of $1.0, 3.0, 5.0$. For a flow with high magnetic flux the radiative forces do not considerably affect the collimation degree. For a flow with low magnetic flux, the dynamical effect of radiative forces is greatly increased. We further find that the line-force parameter $\alpha$ is critical in determining the magnitude of the line-driven forces. Lower values of $\alpha$ lead to an efficient radiative force from the central star and thus de-collimate the flow to a larger extent as compared to higher values of $\alpha$. We find that the radiation forces may also change the mass flow rates in the jet. Even a small change in $\alpha$ may lead to significant changes in mass flux of up to $\simeq 28\%$. In the examples investigated, the line forces due to the hot accretion disk do not play a significant role in controlling the dynamics of the MHD outflow, simply because they are orders of magnitude smaller than all other forces that affect the flow dynamically. This might be different in disk jets from AGN which are less dense and more ionized.

5. Jet rotation driven by MHD shocks in helical magnetic fields

Finally, we propose and numerically investigate the hypothesis that a rotation of astrophysical jets can be caused by magnetohydrodynamic shocks in a helical magnetic field (see [20] for details). Shock compression of the helical magnetic field results in a toroidal Lorentz force component which will accelerate the jet material in toroidal direction. This process transforms magnetic angular momentum (magnetic stress) carried along the jet into kinetic angular momentum (rotation). Hints of such a mechanism were observed in numerical simulations by [21, 22, 23], but were not discussed in great detail, or even applied to observations.

In our simulations the jet is injected into the ambient gas typically with zero kinetic angular momentum (no rotation). Different dynamical parameters for jet propagation are applied such as the jet internal Alfven Mach number and fast magnetosonic Mach number, the density contrast of jet to ambient medium, or the external sonic Mach number of the jet. Figure 5 show the time evolution of the rotational velocity in a propagating jet with time-dependent mass injection. It is clearly visible the rotational velocity is increased at the (internal and external) shock positions. The enhanced rotational velocity coincides as well with the locations of enhanced toroidal Lorentz force [20]. For the example of protostellar jets, the numerically derived rotation feature looks consistent with the observations, i.e. rotational velocities of 0.1-1% of the jet bulk velocity.

The mechanism we suggest should work for a variety of jet applications, e.g. protostellar or extragalactic jets, and internal jet shocks (jet knots) or external shocks between the jet and ambient gas (entrainment).

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