Magnetic acceleration and instabilities of astrophysical jets

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1 Introduction

The first record of an astrophysical jet was made by Curtis (1918), who noticed a “curious straight ray” poking out of the galaxy M87. More than three decades later, Baade & Minkowski (1954) correctly interpreted the feature as an “ejection from the nucleus” to which they referred as “jet”. Since then, many jets have been found and our understanding of the underlying physical processes has advanced considerably.

Most generally, an astrophysical jet may be defined as an elongated high-velocity outflow of gas. One of the most distinctive features of jets is the high degree of collimation, which sets them apart from more isotropic outflows like stellar winds. Their properties, as well as those of the objects from which they emanate, vary considerably. Yet the underlying physical processes are probably very similar in all cases, involving the infall of matter (accretion) onto a central mass and the conversion of rotational energy into an outflow by means of a magnetic field. The differences in the properties are then mostly a matter of scale; the most compact objects produce the fastest and biggest jets.

Much has to happen before a jet appears on the sky. Most jets seem to be launched by an accretion disk, which by itself is an extensive physical problem with many yet unsolved issues. The transition region between the disk and the jet determines the amount of mass flowing in the jet, but is poorly understood to date. We know how jets can be accelerated and collimated by means of a magnetic field. However, most models do not take into account magnetic instabilities, that is to say growing perturbations which destroy the symmetry of the jet and potentially cause a decay of the magnetic field. This is one of the main topics of the present thesis. Radiation can be produced by the jet in many ways, including synchrotron light, Compton scattering and thermal emission. Shocks at the boundary to the external medium as well as within the jet itself play an important role in this context.

A global numerical treatment of the (disk-)jet problem is not feasible in the foreseeable future, as most jets cover many orders of magnitude in distance from their source. In a quasar jet, for example, the jet as seen at radio wavelengths has a size on the order of 1 megaparsec, some $10^{10}$ times larger than the source region (a few astronomical units, say). The expected time scales of (magnetohydro-)dynamic processes in the jet range over the same factor. Direct, time-dependent, 3-dimensional numerical simulations of such large objects are thus out of question. Yet, it is quite likely that the observed properties of jets, like their power, speed, width and emitted radiation depend on time-dependent, 3-dimensional MHD processes. The question is thus where in the 10 decades these processes take place, and how to meaningfully isolate them. From the results presented here it is concluded that
much of the physics determining the observed properties probably happens in the first 3 decades from the source, but not less. A method is applied to deal with this range numerically with existing computational resources.

### 1.1 Types of Jets

Jets emanate from a variety of astronomical objects, including galactic as well as extragalactic sources. The attempt to classify them according to observational features has produced a plethora of names. From a theoretician’s point of view, however, it is most convenient to distinguish jets by their physical origin. Observations are in general too coarse to give direct insight into the inner workings of the respective sources. Still, the basic elements to be included in a physical model are well established in most cases and shall be used here for a classification.

Some jets are observed at the birthplace of stars, the **young stellar objects** (YSOs). There, stars are produced in giant molecular (H$_2$) clouds when gas collapses due to self-gravity. As the central condensation of the cloud grows, it devours the surrounding gas via an accretion disk. Jets emerge along the axis of rotation of the disk with typical velocities of several 100 km s$^{-1}$ per second, comparable to the escape speed from the central protostar. As the jets collide with nearby clouds of gas
1.1 Types of Jets

and dust, they create the complex nebular patches in H$\alpha$ images which are known as Herbig–Haro objects. The overall length of such a protostellar jet is on the order 1 pc, the length-to-width ratio at the largest scale is typically 10 : 1 or more.

In binary systems, it can happen that the more compact component accretes matter from its companion. An accretion disk forms around the growing component and a jet is launched along the axis of rotation. Many such systems are luminous in the X-ray band, for which they are called X-ray binaries (XRBs). The properties of the observable light emission and the jet depend largely on the composition of the binary. Microquasars occur when the accretor is very compact, e.g. a neutron star or a black hole. They produce jets with relativistic velocities.

Relativistic jets also emanate from active galactic nuclei (AGNs), a class of luminous and compact objects found in the center of galaxies. The above-mentioned jet from M87 is a famous example. The now-established standard picture of an AGN includes a black hole with an accretion disk, a surrounding torus of gas and dust, clouds of gas at various distances that produce emission lines, and a well-collimated jet along the axis of rotation of the disk, often accompanied by an opposing counterpart. The observable properties are dependent on the viewing angle. AGN jets excel in speed and extension, having typical Lorentz factors of $\Gamma \sim 10$ and lengths of up to several 100 kpc. Some are remarkably straight and end in spots of high radio emission, others have a meandering shape and grow dimmer with distance from the central source.

The fastest known jets cannot be seen directly. Their existence is inferred from observations of $\gamma$-ray bursts (GRBs) in distant galaxies. The large observed luminosities and rapid fluctuations in the light curves imply that the source of GRBs would be optically thick because of $\gamma\gamma \rightarrow e^+e^-$ pair production, and the observed radiation would be unable to escape unless ultra-relativistic motion with $\Gamma \gtrsim 100$ is involved. Energetic considerations and features in the afterglow (a slowly fading emission after the burst as the jet coasts into the interstellar gas) point to a jet rather than a spherical outflow. If this is indeed the case, then the total energy release in GRBs is on the order of $10^{51}$ erg, a value which is typical for supernovae. The prevailing idea for most GRBs is that their energy is liberated when the fast-spinning core of a massive star collapses to a black hole. The exact circumstances of how a jet with the required properties is generated in this scenario are currently not known. The mechanism that produces the jet must be highly efficient to produce the observed energy output. Moreover, the model has to account for the rapid fluctuations in the light curves of GRBs.

Environment The nature of the environment into which a jet propagates can vary. Close to the source of the jet, the gravity of the central compact object dominates and presumably produces a stratified atmosphere in which the density decreases monotonically with distance from the center. At larger distances, the jet interacts with an interstellar or intergalactic medium. In AGNs, one expects the presence
of clouds which produce the observed line emission; these could interact with the flow (Poludnenko et al. 2002). GRB jets, which are produced in the core of a massive star, may have to drill through a surrounding stellar envelope. Moreover, there is evidence that protostellar jets interact with the still infalling molecular cloud that feeds the accretion disk of the protostar (Velusamy & Langer 1998). Some protostellar jets appear to be deflected as they hit dense clouds (Reipurth & Bally 2001). The movement of the jet-producing object must also be taken into account in some cases. Many AGN jets in galaxy clusters have a bent morphology, caused by the motion of the host galaxy through the intra-cluster medium (head-tail galaxies, Sarazin 1986). A similar situation arises when jets from XRBs are subject to the ram pressure of the interstellar medium (Heinz et al. 2008).

In simulations, the ambient medium must be assumed to have a certain (i.e. minimal) density for numerical reasons. Interactions of the jet with the environment are therefore always of importance. From the calculations presented in this thesis (particularly those in Chapter 4), it seems that apart from pure hydrodynamic interactions, e.g. shock waves in the ambient medium, there are “wiggling” interactions associated with the magnetic field.

1.2 Magnetically Driven Flows

The idea of jets driven by magnetic forces goes back to Bisnovatyi-Kogan & Ruzmaikin (1976), who showed that jets could be the result of rotation acting on a suitably shaped magnetosphere of an accretion disk. To date, this is the most viable concept to explain all the specific properties of jets like their high velocities and strong collimation. Indirect observational support of the magnetic theory comes from the fact that many jets appear magnetized on the scales where this can be investigated. The synchrotron radio emission observed in extragalactic jets, for example, is possible only if there is a magnetic field.

The key element for driving jets magnetically is a magnetic field that is anchored in a rotating object, e.g. an accretion disk. In the simplest case, the anchoring field has only a poloidal (in the direction of the axis of rotation or away from it, but not around it) component and extends out to infinity. The rotation produces an additional toroidal (azimuthal, around the rotation axis) field component. In other words, it twists the magnetic field. The toroidal field contains free energy which gets transformed into a flow.

Within the framework of magnetohydrodynamics (MHD), the acceleration can be attributed to the magnetic pressure gradient associated with the toroidal field \( B_\varphi \). Under the assumption of azimuthal symmetry, the component of the Lorentz force in the direction of the poloidal field \( B_p = B_R \hat{e}_R + B_z \hat{e}_z \) is

\[
F_p = - \frac{1}{8\pi} \nabla_p B_\varphi^2 - \frac{B_R}{B_p} \frac{B_\varphi^2}{4\pi R}
\] (1.2.1)
with \( \nabla_p = \hat{e}_p \cdot \nabla \), where \( \hat{e}_p = B_p / B_p \) denotes the poloidal unit vector. \( r \) and \( R \equiv r \sin \vartheta \) denote the distance from the source (spherical radius) and the distance from the central jet axis (cylindrical radius), respectively. If the flow expands, \( B^2_\varphi \) decreases and the magnetic pressure force (first term in Eq. 1.2.1) points in positive, outwards direction, whereas the magnetic tension force (second summand) points in negative, inwards direction. The two forces cancel each other in the case of ballistic (i.e., rectilinear with constant speed in all directions within the flow) expansion, in which case \( B_p = B_r \) and \( B_\varphi \propto r^{-1} \) due to magnetic flux conservation. In general, one has to solve the full problem to see whether the gradient of \( B^2_\varphi \) prevails over the magnetic tension force to accelerate the flow.

In a frame that corotates with the central rotator, the acceleration can alternatively be attributed to a centrifugal force. This is an elegant view of the acceleration process if it can be assumed that the magnetic field is sufficiently strong to enforce approximate corotation of the plasma, which holds typically up to the Alfvén radius in many models. The centrifugal picture is mathematically equivalent to the magnetic picture described above, but is more limited in scope. Corotation may break down long before the Alfvén radius, for example, if the mass flow is high and the magnetic field weak.

**Further Acceleration via Dissipation**  The rotation-induced acceleration ceases to be effective at a finite distance, usually when the flow reaches the Alfvén or fast magnetosonic speed, and the flow becomes ballistic. To break the balance between the pressure and tension force and produce further acceleration, \( B_\varphi \) must decrease more rapidly than in a ballistic expansion. This happens if it is dissipated along the flow, so that the magnetic pressure gradient becomes steeper. Dissipation occurs naturally as a result of instabilities associated with \( B_\varphi \). An elegant view of this effect can be made if one regards the Poynting flux in the jet as a flux of a “magnetic enthalpy” rather than energy. This gives an alternative interpretation of the fact that the Poynting flux in MHD contains twice the value of the magnetic energy \( B^2_\varphi / 8\pi \). As the magnetic field is dissipated, half of the magnetic enthalpy is turned into heat which, in turn, may be radiated away instantly (if the optical depth is low) while the other half does accelerative work.

**1.2.1 Modeling**  Most theoretical work on MHD outflows relies on simplifying assumptions, each of which has shortcomings in view of the real situation. Above all, numerous authors assume that the flow is axisymmetric and stationary. Examples are the solutions of Sakurai (1985, 1987), which describe stellar/disk winds that, albeit slowly, collimate towards the rotation axis. In the seminal work of (Blandford & Payne 1982), the jet is additionally assumed to be radially self-similar and “cold” (pressure-less). With the self-similar ansatz, the jet extends formally to infinity in
lateral direction. In the case of relativistic jets, it is possible to neglect the Lorentz force under certain circumstances (Fendt et al. 1995). Although this force-free approach does not account for the acceleration, it is argued that the obtained field structure is not too different from what would be needed for that. A most convenient simplification is to consider the poloidal field to be given and fixed at all times. This allows the problem to be tackled analytically to a large extent (see e.g. the review in Spruit 1996).

**Simulations** The stationarity assumption has limits, of course, since it does not allow a description of the jet’s head plowing through the atmosphere when it is fired off. Even after the starting phase, many jets do not settle into a complete steady state. Rather, they contain moving structures such as “knots” of increased light emission. The time-dependent treatment of the jet problem is computationally expensive even if axisymmetry is assumed. Therefore, some authors consider only the propagation of the jet through the ambient medium, using a nozzle with high-velocity gas as a boundary condition to inject the jet into the computational domain (e.g. Kössl & Müller 1988). To learn something about the magnetic acceleration, one has to at least include the accretion disk as a boundary condition (e.g. Ustyugova et al. 1995, and the simulations presented in this thesis). Simulations that include a (simplified) disk (e.g. Hayashi et al. 1996) can cover only its immediate environment. The ultimate goal would be for simulations to cover both the accretion disk as well as the atmosphere which contains the jet, with all the relevant physics being included (e.g. turbulence in the disk). The main problem here is that the contrast in length and time scales is much too high, requiring an unaffordable amount of computational power. For the time being, we have to content ourselves with studying parts of the whole problem.

**1.3 Magnetic Instabilities**

Jets are prone to a variety of instabilities. The most important of these are caused either by the motion relative to the ambient medium or by a strong toroidal magnetic field in the jet, see also the introduction in Sect. 2.1 and the references given there. The present work is mainly concerned with the latter class of magnetically driven instabilities, which have also been a long-standing issue in the attempt to build viable devices for controlled nuclear fusion.

Although better described as truncated cones in many cases, jets may be regarded as plasma columns as a first approximation. The equilibria of such columns are well-studied in the context of controlled fusion (for a sound introduction, see Freidberg 1987). For the column to be in equilibrium (in the absence of external forces), conservation of momentum implies that the sum of the gas and magnetic pressure forces must be matched by the magnetic tension force of the azimuthal field $B_\phi$, which is directed towards the axis. Configurations with only longitudinal fields
Figure 1.2: Modes of perturbations of a cylindrical surface. The instability associated with a $m = 1$ perturbation is found to be one of the most dangerous for fusion plasmas. It is also highly relevant to astrophysical jets containing twisted magnetic fields.

are possible and turn out to be stable, but self-confinement requires the presence of a non-zero $B_\phi$ that causes instabilities. In the laboratory, an azimuthal field arises when a longitudinal current is sent along the column. Presumably for this reason, the term “current-driven” has been adopted and is widely used to denote this class of instabilities.

Perturbations of a plasma column are usually described by a displacement vector $\xi(\varphi,z)$ which is defined at any point of the perturbed surface $R = \text{const}$. An arbitrary $\xi$ can be written as a Fourier series with the modes being proportional to $e^{i(m\varphi+kz)}$ (provided periodicity in $z$). Fig. 1.2 shows examples. For perturbations with $m = 0$, a so-called sausage instability may arise as the tension force of the azimuthal field increases by the radial contractions. In the $m = 1$ case, the magnetic field strength, and thus the magnetic pressure, of the perturbed $B_\phi$ is increased at the inside of the kinks (denser field lines) and decreased at the outside, causing
the perturbation to grow. The susceptibility for these kink instabilities grows with increasing \(|B_\phi/B_z|\), i.e. with decreasing pitch of the helical field lines. Also, the linear growth time is inversely proportional to the strength of the azimuthal field.

**Immediate Consequences for a Jet** The consequences of MHD instabilities are usually catastrophic in the case of fusion plasmas, destroying the fragile state of confinement that keeps the heated gas away from the walls of the fusion reactor. In view of the large extents of astrophysical jets, this rises an immediate concern for the “survival” of jet flows affected by such instabilities. The apprehension is that the jet is distorted to such an extent that it dissipates into its surroundings. If this were to happen at small distances, which is most likely the location where the magnetic field attains enough twist to become unstable, then the magnetic model would not be able to explain the large jets that are observed.

The evolution of MHD instabilities in expanding jet flows, however, is fundamentally different from that in non-moving laboratory plasmas. The continuous expansion of the flow works against the growth of the instabilities. Moreover, the dissipation of the toroidal magnetic field deprives the instabilities of their driving force, preventing an indefinite growth of the perturbations. The jet can become somewhat wider than it would without instabilities, but the bulk kinetic energy persists. It is thus possible that, due to the decay of the toroidal field, a jet of magnetic origin ends up as an ordinary hydrodynamic flow.

Not being fatal, the deformations in the jet can manifest themselves in distinctive structures at observable scales, e.g. the wiggles seen in some protostellar jets. It would seem natural to identify wiggles in observed jets with the displacements expected from (linear) instability. The results in Chapters 2 and 3, however, show that the wiggles have significantly larger scales as a result of nonlinear development of the instability. The features are frozen in the flow when the growth of the perturbations stop and are transported outwards by the then-ballistic flow.

### 1.4 Magnetic Reconnection

As the magnetic field structure gets perturbed by instabilities, abrupt jumps in the polarity of the magnetic field can arise. This causes a decay of the magnetic field, in particular of the toroidal component \(B_\phi\). As pointed out in Sect. 1.2, the decay has consequences for the acceleration of the flow. The magnetic pressure gradient along the jet steepens and, taken as an isolated effect, boosts the acceleration of the jet. The lateral structure of the jet, in particular the poloidal field, is also affected by the decay of \(B_\phi\). This also has consequences for the acceleration behavior. The dynamical evolution of a jet with non-axisymmetric instabilities is thus fundamentally different from a stable, axisymmetric one.

The details of reconnection in astrophysical settings is still a somewhat open issue. Different models exist which are not easily reconciled with the observed rates.
of reconnection (Kulsrud 2001). In ideal MHD simulations such as presented in this work, reconnection is made possible by the numerical diffusion resulting from interpolations (see Sect. A.1 for an overview on the numerical methods). Where fields of different direction are compressed into a grid cell by the evolution of the flow, only their average appears in the next time step. Leaving reconnection to discretization errors thus effectively assumes it to be fast. A popular model for reconnection is that of Petschek (1964), which yields a flow towards the reconnection point at some modest fraction of the Alfvén speed. This is closer to rates resulting from numerical diffusion than the (also popular) Sweet–Parker type models (Parker 1957; Sweet 1958), which yield much slower speeds. Observations of the solar corona indicate a fast reconnection rate (exemplified by the generally modest deviations from a potential field configuration). This is sometimes used as an argument in general for a fast reconnection rate in astrophysical cases. We implicitly make the same assumption in the present work. It should be noted, however, that there are well-documented cases where this assumption is violated (e.g. the MRI simulations presented by Fromang & Papaloizou 2007).
1.5 Summary of Main Results

- With a specifically tailored numerical grid, magnetohydrodynamic jets have for the first time been simulated in three dimensions with very large ranges in distance. The biggest simulations cover a length of 1000 times the source size.

- The magnetic acceleration is fairly efficient. Most of the magnetic enthalpy associated with the twist of the magnetic field is converted to kinetic energy.

- The jets are subject to kink instabilities. The severity of the instabilities depends on the jet’s collimation behavior and on the rotation which produces the twist in the magnetic field: an opening angle that decreases with distance and rigid rotation favor their growth.

- Contrary to the apprehensions voiced in the literature, kink instabilities do not “disrupt” a jet. Rather, they cause a decay in the magnetic field and the jet continues as a ballistic flow, though they can widen the jet by a moderate factor. The actual disruption of a jet requires a strong interaction with the medium into which it propagates.

- The dissipation of the magnetic field induced by the instabilities liberates energy that can be radiated away, making the jet flow visible. The distortions in the jet flow found in the simulations may explain some of the knots and wiggles in observed jets.

- The mechanism by which the Poynting flux of the jet is converted into kinetic energy is different in 3 dimensions from the 2-dimensional (axisymmetric) calculations that have dominated the literature, though their overall efficiency turns out to be similar. In 3D, the flow is driven by a magnetic pressure gradient resulting from the decay of the toroidal field by instabilities, in axisymmetry it is a “diverging nozzle” effect. The lateral structure of the accelerated flow is different in the two cases.

- Jets can be accelerated with (twisted) large-scale poloidal fields or with small-scale magnetic loops. In the latter case, it is essential that the footpoints of the loops are rotating differentially to generate the necessary twist in the field.