Acceleration and emission of MHD driven, relativistic jets

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Abstract. Strong magnetic fields can efficiently extract rotational energy from compact objects launching the relativistic jets observed in active galactic nuclei (AGN), microquasars and gamma-ray bursts (GRBs). Magnetohydrodynamical (MHD) acceleration of jets in the ideal MHD limit is not an ultra-efficient process. This makes internal collisions an unlikely mechanism for the jet emission. I argue that non-ideal MHD effects may both boost the acceleration efficiency and power the jet emission. I show that much of the GRB and blazar phenomenology can be understood as result of magnetic dissipation and that the early afterglow phases from GRBs appear to support the picture of MHD driving.

1. Introduction

Relativistic jets have been extensively observed from supermassive black holes in active galactic nuclei (AGN), solar-mass compact objects in binaries (microquasars) and gamma-ray bursts (GRBs). The theoretical paradigm for jet formation has been developed since the late 70s and can account in a unifying manner for all these sources. It envisions that jets come from strong magnetic fields that thread rotating objects (neutron stars, black hole ergospheres, or accretion disks) extracting their rotational energy (Bisnovatyi-Kogan & Ruzmaikin 1976; Blandford 1976; Blandford & Znajek 1977; Blandford & Payne 1982; for a review see Spruit 2010).

Despite substantial theoretical and observational progress in the field, we still lack a coherent connection between the jet dynamics and emission. Modeling of the acceleration of jets does not deal with the dissipative and emission processes. On the other hand, most of the theoretical work on the jet emission assumes emitting blobs of prescribed properties. Such studies, though informative for the properties of the emission region and the radiative mechanisms, cannot address which processes accelerate the particles. Often, internal collisions are invoked for the energy dissipation assuming (in contrast to the findings of MHD studies) that the acceleration of the jet is complete or almost complete.

I focus, here, on a different approach to the problem of jet emission that attempts to properly take into account the MHD nature of jets. Magnetic fields are considered to be dynamically important at the ejection region and likely remain important at the location of emission. I advocate that magnetic dissipation plays a critical role in both jet acceleration and emission. These considerations can be applied to both blazar and GRB jets providing common insights to the two, phenomenologically different, sources. Finally, I discuss how the residual magnetization of the jet at large distance affects the onset of the afterglow emission of GRBs.
2. Acceleration of MHD jets

For any flow to acquire relativistic speed, it must be clean, i.e., it must be launched with high energy to rest mass ratio. In MHD models\(^1\) most of the energy is initially in the magnetic field: \(\sigma_{in} \gg 1\), where \(\sigma_{in}\) is the magnetization as defined by Michel (1969) or, equivalently, the “baryon loading” of the flow (\(\sigma_{in}\) also stands for the maximum Lorentz factor to which the jet can potentially be accelerated). Further out the flow accelerates converting part of the magnetic energy into kinetic. During this process the bulk Lorentz factor \(\Gamma\) increases while the magnetization \(\sigma\) decreases. A large theoretical effort is devoted in calculating the efficiency with which the flow is accelerated. It turns out that, in relativistic flows, the efficiency of magnetic conversion is, at most, modest with the jet remaining strongly magnetized at larger distances where the emission takes place.

2.1. Ideal MHD acceleration

Acceleration of non-relativistic jets is rather efficient; the flow approaches its terminal speed close to the Alfvén radius (distance where the flow speed equals the Alfvén speed) where much of the magnetic energy is converted to kinetic (e.g. Blandford & Payne 1982). This is not the case for relativistic flows. Assuming an axisymmetric rotator (dipole field and rotation axis aligned), steady 1D relativistic MHD flows are only accelerated up to an asymptotic Lorentz factor \(\Gamma \sim \sigma_{in}^{1/3}\) while the ratio of magnetic to kinetic energy remains high \(\sim \sigma_{in}^{2/3}\) (Michel 1969; Goldreich & Julian 1970; Beskin, Kuzmatova & Rafikov 1998). Rapid variations of the flow at the source can somewhat help to achieve further acceleration (Contopoulos 1995; Granot, Spitkovsky & Komissarov 2010; Lyutikov & Lister 2010).

2D ideal MHD calculations show that, depending on the shape of the jet, acceleration may be more efficient (Begelman & Li 1994; Vlahakis and Königl 2003, Komissarov et al. 2009, Lyubarsky 2009; Tchekhovskoy, Narayan & McKinney 2010). The acceleration rate is maximized for jet boundaries of parabolic shape. Such collimating boundaries, treated as a conducting wall by the simulations, may physically come from the confining pressure of surrounding gas (e.g. the envelop of the collapsing star, winds from the accretion disk) or external, large scale poloidal fields (Spruit, Foglizzo & Stehle 1997). In some cases, because of acceleration through confinement, the jet can reach a rough equipartition between kinetic and magnetic flux at large distance (the magnetization can approach \(\sigma \sim 1\) there). Lyubarsky 2010 has shown that further acceleration to \(\sigma < 1\) is extremely slow (and not relevant for astrophysical jets). Even for the most favourable conditions for ideal MHD acceleration, bulk Lorentz factors \(\Gamma \sim 1000\) needed to explain bright bursts observed with Fermi (see, e.g., Abdo et al. 2009A) appear hard to achieve with high efficiency.

2.2. Non-Ideal MHD effects

More efficient acceleration can be achieved if one abandons the axisymmetry assumption and considers non-ideal MHD effects. If the magnetic field in the jet is non-axisymmetric, containing small-scale reversals, direct dissipation of magnetic energy through magnetic reconnection is possible. Dissipation steepens the pressure gradients in the flow resulting in additional acceleration. At the same time, about half of the magnetic energy is used for heating of the plasma and can power the jet emission. This counter-intuitive process of acceleration through destruction of Poynting flux is explained in Spruit & Drenkhahn (2004). It is a promising process to boost the acceleration and provide a natural mechanism for the jet emission (see next section).

\(^1\) Alternatives to MHD acceleration can account for specific sources. For example, a viable model for GRB jets may be that of neutrino annihilation (Ruffert et al 1997; Popham, Woosley & Fryer 1999; Chen & Beloborodov 2007). However, the attraction of the MHD mechanism is that it can account for all observed relativistic flows in a unifying manner, negating the need to advocate a different mechanism for each type of source.
Non-axisymmetric fields may appear directly at the jet launching region or, alternatively, develop further out as result of MHD instabilities in the jet. The first situation can be realised if the polarity of the field that threads the inner disk reverses with time. The strong poloidal fields required for the jet launching may be produced locally because of the Parker instability (e.g., Tout & Pringle 1992) or advected by the environment (see, e.g., Spruit & Uzdensky 2005; Rothstein & Lovelace 2008). In both cases, separated regions of opposite polarity in the inner disk can be naturally produced. A characteristic configuration of non-axisymmetric jet at the launching region was studied by Drenkhahn (2002), Drenkhahn & Spruit (2002 see also Coroniti 1990; Lyubarky & Kirk 2001). Drenkhahn (2002) considered an oblique rotator (an object rotating with the magnetic dipole axis inclined to the rotational axis) that leads to a flow with field reversals on a scale of the order of the light cylinder. In this configuration, magnetic energy is dissipated efficiently through reconnection within an (astrophysically) reasonable distance leading to fast jets. Furthermore, most of the energy is dissipated in regions of moderate or small optical depths and can be efficiently radiated away.

The second possibility for the developments of small-scale fields in jets is connected to MHD instabilities of an initially axisymmetric jet. For the strongly magnetized flows discussed here, current driven (kink) instabilities are the most relevant ones (Eichler 1993; Begelman 1998; Nakamura & Meier 2004; Giannios & Spruit 2006). They are particularly relevant after the flow passes through the Alfvén radius where it acquires a strong toroidal field. Plasma with strong toroidal fields is notoriously unstable (Kadomtsev 1966). Whether the instability has enough time to grow and substantially affect the jet structure is not clear. Since kinks are intrinsically 3D, they can be appropriately studied with 3D simulations that cover a large range of lengthscales and timescales. Such simulations are, nowadays, starting to be feasible. Moll (2009; see also Moll, Spruit & Obergaulinger 2008) showed that, in Newtonian MHD, kink instabilities are very efficient in converting the large-scale toroidal fields in a small-scale configurations that favor magnetic dissipation. Initial investigation of instabilities in relativistic MHD jets finds weak effect of the current driven instabilities on the jet structure (McKinney & Blandford 2009). It is an exciting topic to the explored more in the future for different initial and boundary conditions.

3. Jet emission

I, now, turn my attention to processes responsible for the jet emission. The next two sections discuss internal-shock and magnetic dissipation models. The section (3.3) focuses on the implications from the observed variability of jets.

3.1. Internal shocks

A usual assumption for the jet emission is that it is result of internal collisions of different portions of the jet (see Rees & Meszaros 1994, Spada et al. 2001 for GRB and blazar jets respectively). The internal shock model typically considers collisions of unmagnetized fluids (see, however, Fan, Wei & Zhang 2004; Mimica & Aloy 2010). It can explain a good fraction of the observed phenomenology (e.g. Nakar & Piran 2002; Bošnjak, Daigne and Dubus 2009) provided that shocks can efficiently accelerate electrons into a nonthermal (power-law) distribution. The particles are accelerated on a very short timescale (through the first order Fermi mechanism at the shock front) and then cool radiatively through synchrotron and Synchrotron Self Compton (SSC) emission. In this picture, synchrotron emission is usually held responsible for the prompt GRB and synchrotron and SSC for the blazar emission.

One drawback of the internal shock model is that, since it only dissipates fraction of the relative kinetic energy, it generally suffers from low radiative efficiency. Realistic calculations...
Figure 1. Schematic representation of the reconnection geometry shown in a frame comoving with the jet. Right: reconnection region enlarged. Heated and compressed plasma leaves the reconnection region at relativistic speed. Direct emission from the reconnection downstream can power ultra-fast evolving flares similar to those observed in the blazars PKS 2155–304 and Mrk 501. Furthermore, the ejected fast moving blobs can stir turbulent motions in the jet dissipating energy over a larger volume and powering to slower varying blazar and GRB emission.

bring the efficiency of such collisions down to the a ~ 1% level, maybe too low to account for GRB observations (Kumar 1999).

Internal shocks are not a favoured mechanism for jet emission if one takes into account the MHD nature of jets. As discussed above, ideal MHD models predict that magnetic fields are expected to maintain at least equipartition values $\sigma > 1$ at large distances where the emission takes place. Any magnetization $\sigma > 0.1$ greatly reduces the efficiency of shocks in heating the plasma by affecting the MHD shock conditions (Kennel & Coroniti 1984). To make things worse, the magnetic fields are expected to be close to parallel to the shock plane. Such configuration is highly unfavourable for particle acceleration in shocks. In these, so-called, “superluminal” shocks the particles are merely advected in the downstream by the field without entering the 1st order Fermi acceleration process (e.g. Kirk & Heavens 1989). The robust analytic arguments are verified by particle-in-cell simulations that show very weak nonthermal particle acceleration is expected even for low magnetization $\sigma > 10^{-4}$ jets (Sironi & Spitkovsky 2010). No existing MHD model can achieve the required 99.99% conversion efficiency of magnetic energy into kinetic for particle acceleration at the shock to be feasible.

Non-ideal MHD processes may be relatively efficient in destroying magnetic energy and leading to a rather low-$\sigma$ jet that could, in principle, be subject to efficient internal collisions. However, whenever this is the case, most of the magnetic energy has been already released in the dissipative MHD processes. Emission from these processes can easily outshine any shock signatures.
3.2. magnetic dissipation
I consider magnetic dissipation as a far more promising possibility for powering the jet emission (see, e.g., Lyutikov & Blandford 2003; Sikora et al. 2005). Magnetic energy can be efficiently dissipated for appropriate field arrangement via magnetic reconnection. Jets that contain small-scale magnetic field reversals are favorable configurations for reconnection. Magnetic reconnection has two generic outcomes: (1) particle heating/acceleration at the current layer or slow MHD shocks and (2) fast bulk fluid motions of plasma leaving the reconnection region (see Fig. 1). Strongly magnetized plasma (with magnetic energy density higher than its rest mass energy density as expected in relativistic jets) can enter the reconnection region rather cold and exit it relativistically hot and with relativistic bulk motions (Lyubarsky 2005; Zenitani, Hesse & Klimas 2010). When the accelerated particles emit efficiently close to the reconnection region, powerful, fast evolving emission can be produced (Giannios, Uzdensky & Begelman 2009). Furthermore, the energy in the bulk motions of the reconnection outflows can cascade to smaller scales by driving MHD turbulence in the jet. In a turbulent environment, particles can undergo stochastic (2nd order Fermi) acceleration with their typical energy determined by a balance of heating and cooling processes (Schlickeiser 1984; Thompson 1994; Stawarz & Petrosian 2008). Stochastic acceleration (slow heating) processes can play a very important role for the jet emission.

Ghisellini & Celotti (1999) have shown that balance of particle heating and cooling results in a mildly relativistic particle distribution that can go a long way in explaining the prompt GRB emission as result of Compton scattering. This idea has been further explored by Stern & Poutanen (2004) and Pe’er, Meszaros & Rees (2006) for various dissipation/heating prescriptions. We have carried out a radiative transfer calculation for the dissipation profile predicted by the reconnection model of Drenkhahn (2002) assuming homogeneously heated flow (Lazzati & Begelman 2010 relaxed this assumption by assuming localized heating and found qualitatively similar results). Our calculations for the emission expected from gradual dissipation models for GRB flows (Giannios 2006B; Giannios & Spruit 2007) showed that the model can naturally explain all the main features of the prompt emission spectrum in the energy range where it is typically observed (i.e. from X-rays to MeV γ-rays; see Fig. 2): the steady sub-MeV break and the spectral slopes below and above the break. Furthermore, comparison with multi-frequency observations of the the prompt emission from GRB 061121 that span from the optical to ∼ MeV range support the model (Giannios 2008). In general, gradual dissipation results in two main emission components: one that comes from layers with Thomson optical depths τ ∼ 1 and one from the Thomson thin region. The first component is the result of thermal seed photons upsattered by hot electrons close to the photosphere of the flow and appears in the X-ray and γ-ray bands. The second component is the combined result of (partially self absorbed) synchrotron emission and inverse Compton scattering and dominates the observed radiation in the optical and ultra violet and contributes to the ∼ GeV emission.

In its current form, the model predicts a exponential cutoff of the emission at ∼ 1 GeV and therefore cannot account for the multi-GeV emission observed in several Fermi-LAT bursts (e.g. Abdo et al. 2009A). However, there is strong evidence that the GeV emission has spectral and, most important, timing properties different from the sub-MeV one (e.g. Abdo et al. 2009B; Ghisellini et al. 2010). The mechanism responsible for the GeV emission is possibly not internal to the jet but related to the shock that the jet drives into the external medium (forward shock; see, e.g., Kumar & Barniol Duran 2009; Ghisellini et al. 2010).

3.3. Variability
Internal shock models rely on variability imprinted to the flow from the central engine (or from its collimation phases) for the emission (Nakar & Piran 2002). The central engine and therefore the jet emission can potentially vary on timescales as short as the light-crossing time (or dynamical
Figure 2. Resulting spectrum (in the central engine frame) from the gradual energy release model for GRB flows (Giannios 2008) compared to the typical GRB spectrum (schematically shown with the dashed line; e.g., Band et al. 1993). From bottom to top the curves correspond to initial magnetization (or baryon loading) $\sigma_{in}$ = 250, 350, 460, 590, 1000 respectively. The stable $\sim$ 1MeV break (shaped from the photospheric component) is followed by a flat $\nu \cdot f_{\nu} \propto \nu^0$ emission. The high $\sigma_{in}$ models have bright UV emission (synchrotron component) and slope $\nu \cdot f_{\nu} \propto \nu^1$ below the MeV break (SSC emission).

time) of the compact object. The same is true in the reconnection model of Drenkhahn (2002) in which magnetic dissipation takes place close enough to the central engine. In this case there is a direct correspondence between the jet emission and the instantaneous luminosity of the flow (Giannios & Spruit 2007; See Fig. 3). These timescales are compatible with those observed in GRBs and, often (but not always; see following paragraph) in AGN jets.

Magnetic reconnection can potentially result to much faster variability provided that individual reconnection regions contribute substantially to the overall emission. This effect is pronounced when reconnection drives (as expected) fast motions within the jet (Lyutikov & Blandford 2003). The ultra-fast variability (~3-5 min) observed in Mrk 501 (Albert et al. 2007), PKS 2155–304 (Aharonian et al. 2007) may well be explained in the context of reconnection (mini)jets (Giannios, Uzdensky & Begelman 2009; 2010; Nalewajko et al. 2010). The minijets

$^3$ This is not the case for models where the magnetic dissipation is triggered by external interactions of the jet (Lyutikov & Blandford 2003; Thompson 2006). In these models the variability is generated in situ.
Figure 3. Narrowing of pulse width with photon energy, as predicted by the magnetic reconnection model for individual sub-pulses of a gamma-ray burst. Both the observed narrowing of the pulses (Norris et al. 1996) and the Amati relation (Amati et al. 2002; Amati 2006) can be explained under the assumption that the relation between luminosity and baryon loading $\sigma_{t_0} \propto L^{0.6}$, holds during the burst.

move faster than the bulk of the jet solving the Lorentz factor crisis (Begelman, Fabian & Rees 2008) that arises for these sources. It worths mentioning that equivalent timescales (shorter than the light-crossing time of the compact object) have not been observed in GRBs. However, they would correspond to sub-µsec variability which we probably do not have the (photon) statistics to detect. Summarising, ultra-fast flaring may be giving us unique probes to the very action of the magnetic reconnection while longer timescale variability is result of variations of the bulk properties of the jet (e.g. luminosity) with time.

4. External interactions
After the jet acceleration and emission phases are complete, the flow interacts with the external medium and slows down. This interaction is believed to give rise to the GRB afterglow emission. The (hydro)dynamics of the deceleration of non-magnetized ejecta has been rather well understood (Sari & Piran 1995; Kobayashi, Piran & Sari 1999). The interaction with the external medium leads to the formation of a forward shock in the external medium and of a reverse shock (RS) into the ejecta. The RS crosses the ejecta on a short time scale leading to a brief emission episode (typically an optical flash). After the RS crossing, the forward shock
Figure 4. R-band light curve of GRB 990123 (Akerlof et al. 1999; Briggs et al. 1999) and GRB 090102 (Gendre et al. 2010; Steele et al. 2009) plotted in the rest frame of the central engine of the burst. Shown are modes which closely match the observed light curves. The $\sigma=0.01$ model (thick lines) has jet bulk Lorentz factor $\Gamma = 640$. The $\sigma=0.1$ model (thin lines) has jet bulk Lorentz factor $\Gamma = 940$. Full, dot-dashed and dashed lines denote the total (forward+reverse shock), reverse shock and forward shock emission respectively. The vertical dashed line approximately shows the time when the polarization of GRB 090102 was measured. The $\sim 10\%$ polarization of GRB 090102 is naturally explained as the combination of highly polarized, dimmer reverse shock and weakly polarized, brighter forward shock emission.

dominates the afterglow emission.

MHD models for GRBs predict ejecta with dynamically important magnetic fields in the afterglow phases. The deceleration phase of strongly magnetized ejecta has only recently been understood. At a first approach to the problem, Zhang & Kobayashi (2005) solved for the shock conditions assuming that a pair of shock forms. Lyutikov (2006) and Genet, Daigne & Mochkovitch (2006) studied the deceleration of high $\sigma$ ejecta. Giannios, Mimica & Aloy (2008) detive the condition for the formation of strong reverse shock and show that even moderate magnetization can suppress the shock, for typical GRB parameters. Relativistic MHD simulations studied the complete deceleration dynamics of ejecta with $\sigma \lesssim 1$ (Mimica, Giannios & Aloy 2009; 2010). Radiative transfer calculation coupled to the simulations gives the resulting synchrotron emission from the shock-accelerated particles. These simulations demonstrate that, for typical GRB parameters, the brightest reverse shock emission is achieved for moderate
magnetization\(^4\) \(0.01 < \sigma < 0.1\) while for \(\sigma \gtrsim 1\) the reverse shock emission is negligible.

Observationally, even after extensive campaigns (e.g., Klotz et al. 2009), only a handful of bursts with evidence for reverse shock emission have been found. GRB 990123 was the first and remains an example (Akerlof 1999). GRB 090102 showed evidence for reverse shock emission which was characterized by polarization of 10\% (Steele et al. 2009). This high polarization degree is not expected from hydrodynamical models that assume small-scale field amplification at the shock.

The paucity of optical flashes-signatures of a RS in the large majority of GRBs can be understood if the bursts are typically characterized by \(\sigma \sim 1\) or higher. The lightcurves of GRBs 990123, 090102 which have detected (what is thought to be) reverse shock emission, may come from jets with somewhat lower magnetization (\(\sigma \sim 0.1\)). Furthermore, the polarization of GRB 090102 is naturally explained as the combination of highly polarized reverse shock and weakly polarized forward shock emission (see Fig. 4). These findings agree well with the predictions of MHD models that strong fields survive at large distance.

Another finding of the Mimica et al. (2010) simulations is that while the bulk of the magnetic energy is transferred into the shocked external medium on a short timescale (comparable to the observed duration of the burst) some magnetic energy (a few \% of the total) remains in the ejecta at least ten times longer that the burst duration. The deceleration of the ejecta may revive MHD instabilities resulting in delayed dissipative events (Giannios 2006A). The residual magnetic energy is sufficient to power some of the X-ray flaring observed in the early afterglow (Nousek et al. 2006; Chincarini et al. 2010). If this interpretation is correct, the X-ray flaring is powered by hot spots in the initial ejecta and does not necessarily imply late time revival of the GRB central engine.

5. (Instead of) Summary
Relativistic outflows have been observed or inferred in various astrophysical settings (galactic centers, binary systems, pulsars, collapsing massive stars). They are likely all emerging from compact objects (black holes or neutron stars). Our best bet for the origin of jets is that they are launched by magnetic fields that extract the rotational energy from the central engine.

Despite the theoretical expectation of a common physical driver of jets, the study of relativistic jets is fragmented both observationally and theoretically. Because of the different phenomenology and involved timescales, different communities observe jets from supermassive black holes, stellar mass compact objects or gamma-ray bursts. Furthermore, theoretical studies of the physics of jets in different scales are typically performed by separate groups. Other groups focus on (a) the jet launching from the compact object, (b) acceleration, (c) emission, or (d) propagation and interaction with the external medium. Despite the fact that in each sub-field there has been substantial theoretical and observational progress, we still lack a coherent and unifying description of the dissipative and emission processes in relativistic jets. Studies of MHD jet acceleration, rarely deal with the dissipative processes that lead to emission while studies for the emission typically neglect the intrinsically MHD structure of the jet.

I argue that one cannot understand the emission of jets without taking into account the main driver of the jet: the magnetic field. The presence of powerful magnetic fields makes internal collisions an unlikely mechanism for powering the emission. Instead, I advocate that similar mechanisms are responsible for the jet acceleration and emission in GRB and AGN jets, directly connected to dissipation of magnetic energy. In this picture, the ultra-fast flaring of blazars may come from plasma leaving from individual magnetic reconnection regions (minijets). Longer

\(^4\) As a discussed in Sect. 3.1, such magnetisation is expected to suppress non-thermal particle acceleration in the shock (and emission over the relevant bands). However, according to the Sironi & Spitkovsky (2010) study, electrons are heated to high energies and can still result in an optical flash when the characteristic frequency of synchrotron emission is close to the optical band.
timescale variability of jets likely tracks the variations of the luminosity of the flow. It can be connected to interactions of the reconnection minijets with the rest of the jet that dissipate bulk kinetic energy on larger volume.

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