Magnetic collimation of the relativistic jet in M 87

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ABSTRACT

We apply a two-zone MHD model to the jet of M 87. The model consists of an inner relativistic outflow, which is surrounded by a non-relativistic outer disk-wind. The outer disk-wind collimates very well through magnetic self-collimation and confines the inner relativistic jet into a narrow region around the rotation axis. Further, we show by example, that such models reproduce very accurately the observed opening angle of the M 87 jet over a large range from the kiloparsec scale down to the sub-parsec scale.

Key words. MHD – methods: numerical – galaxies: jets – galaxies: individual: M 87

1. Introduction

One of the oldest (Curtis 1918) and best studied extragalactic jets is harboured by M 87 in the Virgo cluster. This classical object presents a nice opportunity to test a specific mechanism for jet formation in some detail, namely magnetic self-collimation, first pioneered by Blandford & Payne (1982). Later, a overwhelming wealth of theoretical investigations build upon this model.

At the distance of M 87 ($z = 0.004$, Jacoby et al. 1990) a miliarcsecond of angular scale corresponds to a linear scale of 0.072 pc. The central mass of the AGN is approximately $3 \times 10^9\, M_\odot$ (Macchetto et al. 1997), which translates into a Schwarzschild radius r_g of about 0.0003 pc or 0.0041 mas. Thus at the arcsecond scale, the jet of M 87 has a length of 2 kpc. The jet and its hot spots have been systematically studied across the electromagnetic spectrum from the radio to X-rays, both, with ground-based observations and from satellites (for a review see e.g. Biretta 1996). The jet is clearly detected at mm wavelength with a resolution of 0.009 pc ($30\, r_g$) out to distances of about 2 mas ($500\, r_g$) from the core. The initial opening angle is approximately $60°$ on scales of about 0.04 pc ($100\, r_g$) and decreases rapidly until reaching $10°$ at a distance of 4 pc from the core (Biretta et al. 2002).

These observations suggest, that the jet of M 87 is rather slowly collimated across a length of several parsec (several $10^5\, r_g$). This scale is significantly larger than the radius of the black hole or any of the characteristic orbits, e.g. the last-stable orbit at $6\, r_g$, but well below the size of the accretion disk, which can be as large as 20 pc. Therefore Biretta et al. (2002) conclude that the accretion disk plays an important role in the initial jet collimation. On the other hand, thermal X-ray observations (White & Sarazin 1988) show that the jet is over-pressured, since it is surrounded by gas of a thermal pressure, which is 10−20 times lower than the minimum pressure value required for the synchrotron emission of the jet (Owen et al. 1989). In addition, the projected magnetic field vectors suggest a significant azimuthal component of the magnetic field which can assist in confining the jet. In this work, we provide a specific mechanism which illustrates the assumption that the disk plays a pivotal role in magnetically collimating the jet.

The prevailing view in jet formation theory is that relativistic and non-relativistic jets are magnetically collimated, a view supported by observational evidence (Gabuzda et al. 2004). The toroidal magnetic field generated by the rotation of the jet's base, i.e. the underlying accretion disk, spontaneously collimates part of the outflow into a narrow region around the axis of rotation, as shown by numerous analytical models, e.g. Lovelace (1976); Blandford (1976); Bisnovatyi-Kogan & Ruzmaikin (1976); Blandford & Payne (1982); Heyvaerts & Norman (1989, 2003); Chiueh et al. (1991); Sauty & Tsinganos (1994); Vlahakis & Tsinganos (1998, 1999); Vlahakis et al. (2000). Nevertheless, to calculate the fraction of the collimated mass- and magnetic fluxes, the possible formation of shock waves or the opening angle of the outflow, one needs direct numerical simulation for every specific case (Krasnopolsky et al. 1999; Ustyugova et al. 1999; Kudoh et al. 1998; Gracia et al. 2005, and others).

In Bogovalov & Tsinganos (1999) and Tsinganos & Bogovalov (2000) it was found that, for a uniformly rotating base, only a small part of the total mass- and magnetic flux is collimated cylindrically. This fraction is only about 1% of

the corresponding values of an assumed uncollimated outflow, i.e. before rotation of the base sets in. Recently, this conclusion was confirmed by Krasnopolsky et al. (2003) for outflows originating from an accretion disk. However, observations and theoretical arguments indicate that a higher fraction of mass- and magnetic flux should be collimated inside the jet. A second difficulty of the original magnetic collimation picture is that for relativistic outflows, the degree of collimation of an initially radial wind is extremely small due to the decollimating effect of the electric field and the large effective inertia of the relativistic plasma (Bogovalov 2001).

In a series of recent papers Tsinganos & Bogovalov (2002, 2005) adopted a simple model to demonstrate, that the mechanism of magnetically self-collimation of outflows may also efficiently collimate even relativistic outflows, provided that the system consists of *two components*: an *inner relativistic plasma* originating from regions close to the central source and an *outer non-relativistic wind* originating from, e.g., the surrounding accretion disk (see also Sol et al. 1989). In the particular case studied in Tsinganos & Bogovalov (2002), the toroidal magnetic field in the inner relativistic outflow was negligible by assuming that the angular velocity at its base is negligible. Under such conditions the disc-wind plays the role of the collimator and confines all the relativistic outflow into a collimated fiducial jet around the axis. Steady state solution for such relativistic jets were obtained with Lorentz factors up to $\Gamma = 5$. We stress, that all the magnetic and mass flux at the base of the relativistic plasma is collimated into the relativistic jet.

We apply a similar model to the case of the jet of M 87 to demonstrate, that the magnetic confinement of an inner relativistic outflow by a non-relativistic disk-wind may lead to a slow collimation of the relativistic jet which fits the observations of the opening angle. In the following sections we describe in more detail the model and the numerical method used, apply this to the parameters appropriate to the jet of M 87 and present some results.

2. Model and numerical method

We adopt as a model an axisymmetric outflow consisting of two components, which are implemented as boundary conditions. An inner relativistic outflow, which originates from close to the central black hole, and an outer non-relativistic one, originating from a region which is no longer dominated by relativistic dynamics. This may be realized by a similar two-component structure of the underlying accretion flow consisting of an outer standard disk (Shakura & Sunyaev 1973) and an inner hot flow, which can be either an advection dominated accretion flow (Narayan & Yi 1994; Gracia et al. 2003) or the final plunging region near the black hole, where relativistic dynamics dominates through e.g. frame-dragging or the Blandford & Znajek (1977) effect. We assume that initially radial outflows originate from both regions. In the following we will refer to them as relativistic jet or outflow and (non-relativistic) disk-wind, respectively. Figure 1 shows a cartoon of the model.

The relevant physical properties of these two components are assumed to be given at a spherical launching surface at a distance r_0. We further assume, that most physical quantities
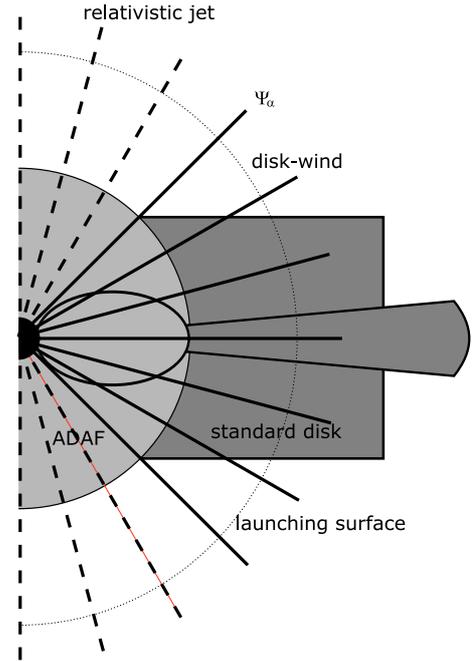

Fig. 1. Illustrative sketch of the model (see text).

have constant values on the launching surface within the two regions, respectively. The only exception is the angular velocity as explained later. The boundary between the two components is given by an angle α measured from the rotation axis. The indices $_j$ and $_d$ designate quantities in the jet and disk-wind component, respectively. The launching surface is threaded by a radial magnetic field of strength B_0. We normalise the magnetic flux Ψ to $\Psi = 0$ on the rotation axis and $\Psi = 1$ on the equatorial plane. The two outflow components are characterised by their temperature in units of the rest-mass energy T and the radial outflow velocity in terms of the bulk Lorentz factor Γ.

For simplicity, the angular velocity ω in the inner relativistic outflow is constant at a value ω_j. In the disk-wind it drops smoothly to zero as given by

$$\omega_d(\Psi) = \omega_j \left(\frac{\Psi_\alpha}{\Psi} \right)^2 , \tag{1}$$

where $\Psi_\alpha = 1 - \cos \alpha$ is the magnetic flux at the boundary between the two components. Further, for simplicity the disk-wind is assumed to be dynamically cold, i.e. $T_d = 0$ and the magnetic field strength at the launching surface to be fixed at $B_0 = 1$ G throughout this paper. This choice leaves us with the set of adjustable free parameters $(\alpha, T_j, \Gamma_j, \omega_j, \Gamma_d)$ and additionally the radius of the launching surface, which is constraint by the numerical method that we use to solve the system of equations.

We apply the same numerical method as Tsinganos & Bogovalov (2002). MHD problems in general can be decomposed into two mathematical regimes, hyperbolic and elliptical. In the hyperbolic regime, the problem can be treated as an initial value Cauchy-type problem, i.e. given the conditions on a specific surface as initial values, the steady state solution of the flow further downstream can be calculated by direct

integration. This is numerically much easier than treating the problem in the elliptical regime. If the local poloidal velocity of the flow exceeds the local speed of the fast-mode Alfvén waves, then the flow is hyperbolic. Therefore, we place the launching surface beyond the fast surface and calculate the physical quantities along the flow by means of the conserved MHD integrals of the flow.

Further, the magnetic field structure is solved self-consistently by means of the transfield equation instead of assuming a given external magnetic field. In this way, we obtain a self-consistent solution of the full, steady-state, relativistic MHD equations, which depends only on the boundary conditions assumed on the launching surface. The latter must necessarily be located beyond the fast surface of the outflow. More specifically, we do not solve the problem inside the launching surface, and a self-consistent solution of the global problem, i.e. including the sub-fast region inside the launching surface, might show, that, in particular, the assumed radial magnetic field inside the launching surface might not be realized.

3. Data basis and fitting results

The model has been applied to the jet of M 87. In particular, we aimed to reproduce the measured opening angle as collected and reported by Biretta et al. (2002). In observations the opening angle of the jet is given by the width of the jet, which in turn is the length scale beyond which the brightness of the jet drops of sharply. Our model does not include any radiative processes and does not have any notion of brightness. Instead, we define the boundary of the jet by a specific magnetic flux line Ψ_α which separates the two components at the launching surface. Everything inside this flux line is assumed to be visible as jet, everything outside is not.

The observations extend from very small length scales of 0.04 pc to much larger scales of 1 kpc. The largest scale data point is actually obtained in regions downstream of the very prominent *knot A* of the jet, which is located at a distance of 12″ (865 pc) from the core. It is generally believed, that the jet outflow dramatically changes character at knot A, either through interaction with the environment or through internal micro-physics. We do not model either of these and therefore exclude any data beyond knot A from our fitting procedure.

Similarly, we might exclude the innermost data point at 0.04 pc. This point is very close to the adopted launching surface at $r_0 = 10^{17}$ cm. As discussed previously, we expect the largest uncertainties in our model close to this surface. In particular, the magneto-centrifugal mechanism is, under generic conditions, most efficient in collimating the poloidal magnetic field near the Alfvénic surface, which is located inside the fast surface. So, in reality, the outflow will collimate even more efficiently near its base, than can be calculated from our current model. To meet the constraint, that the fast surface is within the launching surface, we fix the magnetic field strength to $B_0 = 1$ G.

We present two exemplary models: model A includes the smallest scale in the data set, while the model B does not. Model A fits all data inside knot A, as shown
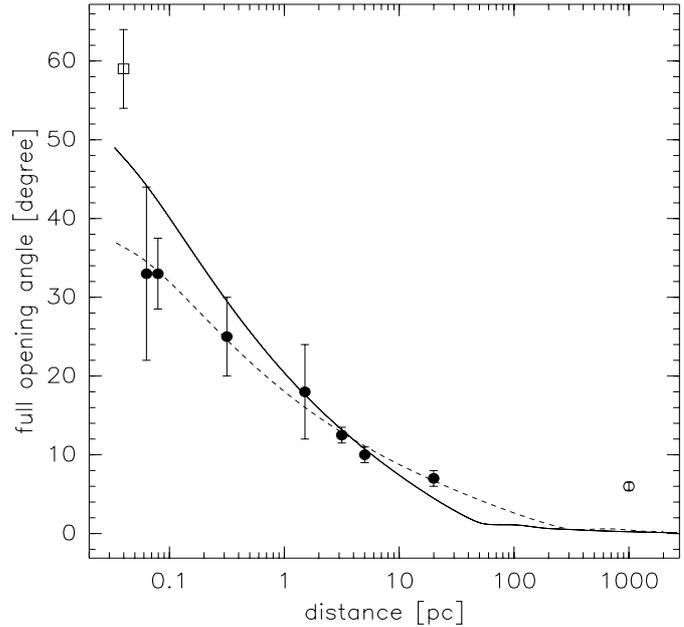
Fig. 2. Comparison of the opening angle calculated from model A and model B, and the observational data for M 87. The *black lines* represents model A (*solid*) and model B (*dashed*), respectively, while various symbols represent observational measurements. The data points marked by *black circles* was taken into account in the fitting procedure for model A and B. Model A fits, additionally, the innermost data point (*open square*). The outermost measurement *open circle* was disregarded for both models, since it is located beyond knot A (see text).

in Fig. 2. The model parameters are $(\alpha, T_\mathrm{j}, \Gamma_\mathrm{j}, \omega_\mathrm{j}, \Gamma_\mathrm{d})_A = (25°, 2.5\, mc^2, 1.8, 2.7\ r_\mathrm{g}/c, 1.02)$. The outflow is only moderately relativistic, both in terms of its internal energy and in terms of its bulk motion with a Lorentz factor of only $\Gamma_\mathrm{j} = 1.8$ or physical velocity $v_\mathrm{j} = 0.83\, c$. A better fit would be obtained if the curve were steeper at the beginning and flattened out at larger distances. Unfortonely, our parameter studies showed, that it is very difficult to obtain such a curve, i.e. to change its curvature. Basically, there are only three degrees of freedom: displacing the curve in the vertical and horizontal direction, and rotation around a pivotal point near the origin. For this reason, the fit to the data points at intermediate distances can be further improved only, if the data point at the lowest distance is not taken into account.

This constraint leads us to model B, which fits all data inside knot A excluding the innermost data point, as shown in Fig. 2. The model parameters are $(\alpha, T_\mathrm{j}, \Gamma_\mathrm{j}, \omega_\mathrm{j}, \Gamma_\mathrm{d})_B = (19°, 2.5\, mc^2, 2.6, 2.7\ r_\mathrm{g}/c, 1.02)$. The initial opening angle is considerably smaller than for model A. This implies a higher magnetic field strength at the boundary between the two zones, which leads to more efficient collimation in the disk-wind and confinement of the relativistic jet. To achieve large opening angles further down the flow, this has to be compensated by a larger effective inertia. This is accomplished through a higher initial poloidal velocity of Lorentz factor $\Gamma_\mathrm{j} = 2.6$, i.e. physical velocity $v_\mathrm{j} = 0.92\, c$. We note however, that a similar effect could also have been accomplished with a lower collimation efficiency of the disk-wind by reducing the angular velocity at its

base, or even by increasing the effective inertia through higher internal energy T_j.

4. Conclusions

The two-zone model presented in this work fits nicely the observed opening angle of the jet of M 87 over at least three decades in linear length scale. It solves two problems of one-zone, magnetic, self-collimation models by sharing the work between the two zones. The inner relativistic zone provides the moderately high Lorentz factors observed in a number of objects, but has a very low collimation efficiency and would thus not result in a cylindrical or conical jet of its own. This job is done by the outer non-relativistic disk-wind. This zone collimates very efficiently and confines the inner relativistic jet to a narrow region around the rotation axis. On the other hand, by itself, it could not attain the necessary Lorentz factors due to its non-relativistic nature.

The single most important ingredient seems to be the balance between effective inertia of the relativistic outflow and the confining force of the outer disk-wind. This equilibrium can be shifted in a number of ways, e.g. towards higher effective inertia by increasing the outflow velocity or internal energy of the relativistic jet or by decreasing the collimation efficiency in the outer disk-wind by reducing the angular velocity. In this way it is possible to produce similar opening angle profiles with a number of different parameter sets.

It is therefore very important to constrain observationally some of the free parameters of the model. One obvious working point is the location of the fast surface, i.e. Alfvénic and bulk velocity near the base, which tells us where to start applying this model. We note further, that Biretta et al. (2002) were never truly able to pinpoint the location of the central object. Hence, their opening angle determinations, even if impressive, are only tentative. This is especially true for the innermost data point. If the central source were further away from the jet, this would strongly decrease the opening angle. Still such a opening angle profile could be easily satisfied by parameters along the lines of model B.

Our model relies on the existence of of two dynamically distinct regions. To communicate ideas, we identified them with an inner ADAF or final plunging region of the flow, and a standard disk. The implementation of this two zones as regions of constant physical quantities, each, is certainly oversimplified. Still, a more realistic picture would share some of the general properties of the discussed model. Even a gradual transition between the two zones seems possible. This is true as long as the outer region is capable of sustaining a self-collimated magnetic field structure through, e.g., the Blandford & Payne mechanism, and the inner region disposes over enough effective inertia to open up its way along the rotation axis with large enough Lorentz factors. In particular, the inner region must not necessarily have negligible angular momentum. In the presence of magnetic fields, rotation could help to adjust the balance between the effective inertia and the magnetic confinement.

Within the present modeling, our studies show, that the observed opening angle of the M 87 jet is best reproduced by models with moderate bulk Lorentz factors, i.e. $\Gamma \sim 2-4$, a range, which is compatible with the currently favoured values (Biretta et al. 1995; Cramphorn et al. 2004; Biretta et al. 1999).

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