Mem. S.A.It. Vol. 79, 1174

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eRMHD simulations of jets with helical magnetic fields

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Abstract. We present numerical magnetohydrodynamic and emission (eRMHD) simulations of relativistic jets in active galactic nuclei. We focus our study on the role played by the magnetic field in the dynamics of the jet, analyzing the balance of the main driving forces which determine the jet evolution. Overpressured jets with different magnetizations are considered in order to study their influence in the jet collimation, confinement and overall stability. Computation of the synchrotron emission from these models allows a direct comparison with actual sources. We find that the relative brightness of the knots associated with the recollimation shocks decreases with increasing magnetization, suggesting that overpressured jets presenting stationary components may have a relatively weak magnetization, with magnetic fields of the order of equipartition or below.

Key words. Relativistic Jets, RMHD, Numerical Simulations

1. Introduction

Recent polarimetric high resolution VLBI observations of jets in AGN show evidence for the existence of helical magnetic fields (e.g., Asada et al. 2002, 2008; Gabuzda et al. 2004; Gómez et al. 2001, 2008). Although it is still largely unknown what is the role played by the magnetic field in the jet dynamics, helical magnetic fields may play an important role in the formation, collimation and acceleration processes.

Thanks to the recent developments in the numerical modelling of magnetized relativistic jets it is now possible to study the influence of the magnetic field in the dynamics of relativistic jets. The computation of nonthermal (synchrotron) emission using relativistic magnetohydrodynamic (RMHD) simulations as input allows us to obtain synthetic radio maps that can be directly compared with actual observations (see, e.g., Gómez 2002, and references therein). The synergy between simulations and observations is a powerful tool in the understanding of the physical processes taking place in jets.

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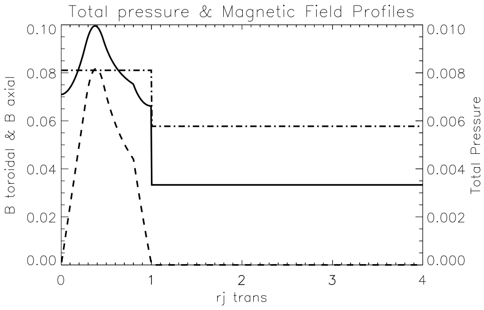

Fig. 1. Toroidal (dashed line) and axial (dash-dotted line) magnetic field profiles for our models. Total pressure (solid line) for a model in equipartion (β=1) is overplotted. The axial units are in jet radius.

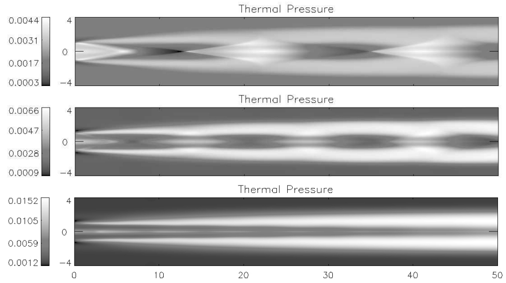

Fig. 2. Thermal pressure for model A_1 (top), A_3 (center) and A_{10} (bottom).

2. eRMHD simulations

The simulations have been performed using a numerical code that solves the RMHD equations in conservative form and cylindrical coordinates with axial symmetry (see Leismann et al. 2005 for more details). Numerical fluxes between contiguous zones are computed using an approximate Riemann solver. Spatial second order accuracy is achieved by means of piecewise linear, monotonic reconstruction of the fluid variables. Averaged values of the conserved variables are advanced in time by means of a Runge-Kutta algorithm of third order. The magnetic field configuration is kept divergence-free thanks to the implementation of a constrained transport method.

2.1. Setting up the numerical simulations

The RMHD simulations have been performed on a 2D grid in cylindrical coordinates under axisymmetry. The grid consists of 512 by 1600 cells covering a domain of 4 by 50 beam radii, i.e., the resolution is 128 by 32 cells per beam radius. The model is characterized by the injection Lorentz factor of the jet Γ, and the specific internal energy, ϵ_b. Two more parameters, the beam to external medium ratios of pressure (κ) and rest-mass density at the injection position, are used to fix the properties of the atmosphere through which the jet propagates. An ideal gas equation is used, characterized by the adiabatic exponent. We have performed simulations of overpressured (κ=2) relativistic ($\Gamma = 4$) jets with different magnetizations β, defined as the ratio of the magnetic to the thermal pressure: model A_1 (β=1), A_3 (β=3), and A_{10} (β=10). When increasing β we reduce the thermal pressure accordingly so that the total pressure of the jet remains constant. The values of the σ parameter (defined as the ratio of the magnetic energy to the mass-energy density) of the models are: model A_1 (σ=0.66), A_3 (σ=1.69) and A_{10} (σ=6.66).

We are assuming a helical magnetic field structure which consists of two components with profiles as shown in Fig. 1 (see Lind et al. 1989; Komissarov 1999). We defined the pitch angle ϕ as the ratio of the mean toroidal mag-

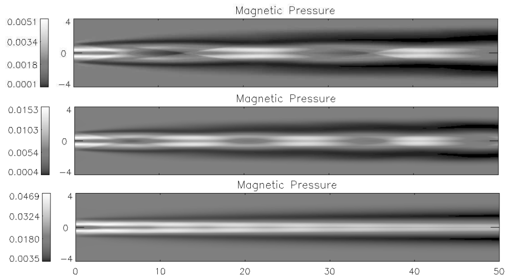

Fig. 3. Magnetic pressure for model A_1 (top), A_3 (center) and A_{10} (bottom).

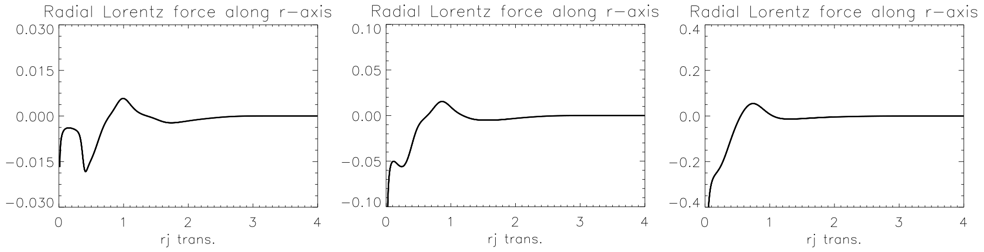

Fig. 4. Panel show radial cuts (at 10 axial jet radius) of the radial Lorentz force for model A_1 (left), A_3 (center) and A_{10} (right).

netic field to the axial one (ϕ=90° is a fully toroidal magnetic field). For the models that we present here we are considering jets with an averaged pitch angle of $\phi = 25°$.

3. The influence of the jet magnetization on the dynamics

The fluid dynamics of the jet is dominated by the tendency of the fluid to approach pressure equilibrium with the external medium. The balance of pressures has two contributions, one due to the thermal gas and the other to the magnetic field.

The initial missmatch of pressure between the jet and the external medium causes overexpansions and overcontractions past equilibrium of the fluid leading to the formation of a pattern of recollimation shocks (see Figs. 2 and 3). The magnetic field, if strong enough, is able to confine and collimate the jet. That is, for values of $\beta \gtrsim 1$ it is the magnetic field which controls the jet dynamics (see also Mimica et al. 2007).

In order to study in detail the jet dynamics we analyze the two main driving forces that govern the evolution of the jet, which are the gradient of the thermal pressure and the Lorentz force. The Lorentz force has the following expression:

$$\mathbf{j} \times \mathbf{B} = \frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B}, \tag{1}$$

where j is the current density and B is the magnetic field. The main component of the Lorentz force is in the radial direction (see Fig. 4): this force is exerted transversal to the direction of propagation of the jet. In the inner part of the jet it is negative, then the force opposes to the expansion of the jet, collimating and confining it. This is the pinching effect of the magnetic field. Jets with higher values of β are not able to expand as much as for lower β, and therefore the subsequent contraction takes place farther downstream. This effect results in jets with weaker recollimation shocks and decreasing radius (see Fig. 2) as β increases.

We observe also that although models A_1 and A_3 mantain their initial collimation, model A_{10} converges (i.e., the jet radius decreases with distance along the jet). Studying in detail model A_{10} we can see how the toroidal magnetic field increases as the jet propagates, and so does the radial Lorentz force (see Fig. 5) along the jet.

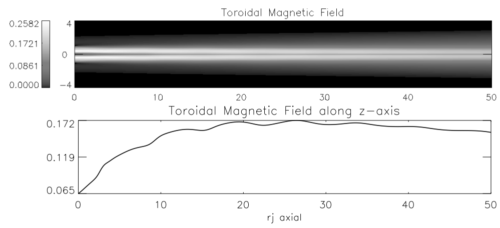

Fig. 5. Panels show toroidal magnetic field (top) and axial cut (at 0.2 transversal jet radius) of the toroidal magnetic field (bottom) for model A_{10}.

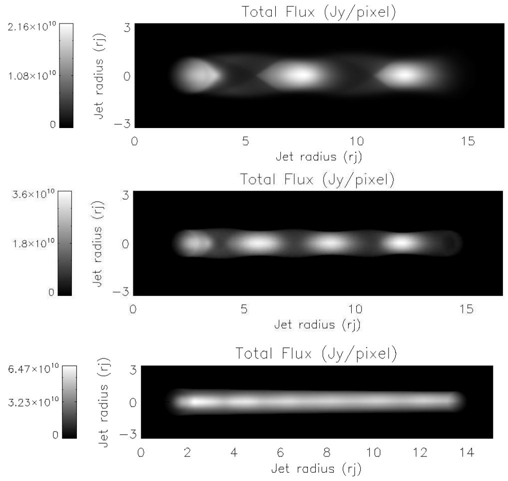

Fig. 6. Panels show total emission maps in arbitrary units for a viewing angle of 14° for model A_1 (top), A_3 (center) and A_{10} (bottom).

4. The influence of the jet magnetization on the emission of recollimation shocks

We are interested in studying the emission of magnetized jets in order to obtain a better understanding of the different types of stationary structures observed on real jets, particularly the suggestion that stationary components in the parsec-scale jets could be identified with recollimation shocks (e.g. Daly & Marscher 1988, Gómez et al. 1995). We have computed total emission for a viewing angle α of 14° for the RMHD models that we have presented. Figure 6 shows that the relative brightness of the knots associated with the internal shocks decreases with increasing magnetization. Indeed, we observe that model A_1 presents strong stationary components with a relative brightness that doubles the emission of the underlying flow. On the other hand, model A_{10}, which has very weak recollimation shocks (see Fig. 2), shows a smooth jet emission with small variations along the jet. We can therefore suggest that overpressured jets presenting stationary components may have a relatively weak magnetization, with β close or below equipartition.

Acknowledgements. This research has been partially supported by the Spanish Ministerio de Educación y Ciencia and the European Fund for Regional Development through grants AYA2007-67627-C03-03 and AYA2007-67627-C03-01. M.P. acknowledges a postdoctoral fellowship of the Generalitat Valenciana (Beca Postdoctoral d'Excel·lència). I. A. has been supported by an I3P contract by the Spanish "Consejo Superior de Investigaciones Científicas".

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