Bending relativistic jets in AGNs

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Abstract: We present simulations of relativistic jets propagating in a nonuniform medium. Specifically, we study the bending of jets propagating obliquely to the vector of the density-gradient. Our results are applied to the NGC 4258, where such a medium is assumed to be provided by the atmosphere of the sub-parsec accretion disk tilted with respect to the original direction of the jet propagation. As a result, the jet is bent on a scale comparable to the density scaleheight of the disk atmosphere. The magnitude of the bending effect is found to be largest for light jets with low Lorentz factors. The predicted direction of bending is consistent with the observations.

Introduction

Begelman & Cioffi (1989) and Cioffi & Blondin (1992) demonstrate that a light jet propagating in a uniform ambient medium can be confined and collimated by the cocoon pressure. However, if the ambient medium is nonuniform then an asymmetric cocoon may develop, resulting in pressure differences on opposite sides of the beam. It is conceivable that this effect may be strong enough to cause a deflection of the beam on a scale comparable to the scale of ambient medium nonuniformities. This can explain bending of relativistic jets on parsec – kiloparsec scales observed in quasars and radio-galaxies (see e.g. Appl et al. 1996, and references therein), or on sub-parsec scales (e.g. in NGC 4258; Herrnstein et al. 1997). In the former case the density-gradient is presumably related to the distribution of matter in the molecular torus (Baker 1997), in the latter case the density-gradient can be

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provided by atmosphere of a warped accretion disk. In the present communication we apply our numerical simulations to the latter case, assuming that the velocity vector of the jet gas at the inlet is misaligned with the density gradient in the atmosphere of the disk (Fig. 1).

Fig. 1. Schematic representation of initial conditions for jet evolution (see text for details).

The observational support for such a scenario is provided by the warped accretion disk discovered in the central region of NGC 4258 (Herrnstein et al. 1997, and references therein). We note that in this case the perturbations on a sub-parsec scale may be responsible for the complicated morphology of the jets on larger (up to kpc) scales on which the jets appear to be composed of several twisted strands (Cecil, Wilson & DePree 1985). The strongly warped disk present in the nucleus of NGC 1068 (Begelman 1997, private communication) may also influence the radio jet morphology in this object (Gallimore et al. 1996), but the evidence is not yet as compelling as in NGC 4258.

An estimate of the pressure difference on opposite sides of the beam may be readily obtained after Begelman & Cioffi (1989); for a more rigorous analysis see Loken et al. (1992). The cocoon pressure, $p_c$, is roughly equal to the total energy deposited by the jet divided by the volume of the cocoon. Assuming that the energy flux in the jet, $L_j$, and the propagation speed of the jet head, $v_h$, are constant in time, and calculating the transversal expansion rate of the cocoon from the strong shock approximation, for cylindrical jets we obtain

$$p_c \propto \left(\frac{\rho_a L_j}{v_h}\right)^{1/2} t^{-1},$$

where $\rho_a$ is the density of the ambient medium in which the cocoon expands. Due to a different dependence of the cocoon volume on time, the corresponding formula for slab jets reads

$$p_c \propto \left(\frac{\rho_a L_j}{v_h}\right)^{1/2} t^{-1},$$
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\[ p_c \propto \left( \frac{L_j}{v_h} \right)^{2/3} \rho_a^{1/3} t^{-2/3}. \]  

Thus, an estimate for pressure contrast on opposite sides of the jet is given by

\[ \frac{p_c^L}{p_c^R} = \left( \frac{\rho_a^L}{\rho_a^R} \right)^{\alpha}, \]

where \( L \) and \( R \) refer to the left and right side of a slab jet \((\alpha = 1/3)\), or to points on opposite sides of the symmetry axis of a cylindrical jet \((\alpha = 1/2)\). The pressure contrast can increase in time as the difference between \( \rho_a^L \) and \( \rho_a^R \) increases as the bow shock propagates sideways. However, one may also expect that the efficiency of the proposed mechanism will decrease with time due to the general decrease of cocoon pressure.

**Numerical Model**

We perform our simulations with the help of the AMRA code which combines the special relativistic hydro-code of Martí et al. (1997) with the AMR (Adaptive Mesh Refinement) approach of Cid-Fernandes et al. (1996). In this study we adopt Cartesian geometry, and a two-dimensional slab representation for the jets. The base grid consists of 40 and 60 zones in \( x \) and \( y \) direction, respectively, and we use two additional levels of grids with refinement ratios of 4. Therefore, the resolution of the finest grid is equivalent to that of a uniform grid of \( 640 \times 960 \) zones.

The jet material is injected into the computational domain parallel to the \( y \) axis, through the inlet located in the middle of the \( x \) axis. The width of the inlet is equal to 2 zones of the base grid, so that a resolution of 16 zones per beam radius is achieved on the finest grid. We use the reflecting boundary condition at the \( x \) axis (to the left and to the right of the inlet), and the transmitting boundary condition otherwise. The central region of an AGN accretion disk is approximated by the ambient medium with an exponential density stratification \( \rho \sim \exp(-l/H) \), where \( l \) is the distance from the mid-plane of the disk. The inlet of the jet is located in the mid-plane of the disk, and the ambient density is not allowed to fall below \( 1 \times 10^{-4} \) of the mid-plane value. The pressure of the ambient medium is constant throughout the grid.

In our units speed of light, beam radius, and ambient density at the inlet are equal to one. The model parameters are the beam Lorentz factor \( W_b \), beam Mach number \( M_b \), proper rest-mass density contrast (beam to ambient medium) at the inlet \( \eta \), pressure contrast \( K \), adiabatic exponent \( \gamma \), tilt angle \( \theta \) between the mid-plane of the disk and the \( x \) axis, and density scaleheight \( H \). Here we consider only pressured-matched \((K = 1)\) jets with \( \gamma = 5/3 \). Further, we restrict our attention to light \((\eta = 0.01)\), highly–supersonic \((M_b = 6)\) jets which develop large overpressured cocoons (Martí et al. 1997) required for our bending mechanism to be efficient.

For jets with high internal beam Mach numbers and the same beam densities, jet luminosity, \( L_j \), is proportional to \( W_b^2 \). According to equations (1) and (2),
the cocoon pressure is proportional to $L_j$ raised to the power of 1/2 or 2/3 for cylindrical and slab jets, respectively. Therefore, the net bending force (i.e., the cocoon pressure gradient) acting on the beam will be proportional to $W_b$ raised to the power of 1 (cylindrical) or 4/3 (slab). Since the resistance of the jet to bending is proportional to the momentum density, which for relativistic flows scales with $W^2$, the bending mechanism will be less efficient for highly relativistic flows. Thus, $W_b$ should not be too large and we adopt $W_b = 6$. Finally, since tilt angles in excess of 45° are rather unlikely, we adopt $\theta = 30°$.

Results

We present three models with different $H$, of which model A ($H = 5, \theta = 0°$) serves as the reference model for models B ($H = 2, \theta = 30°$) and C ($H = 5, \theta = 30°$). For these models, Figs. 2 and 3 present the rest-mass density and gas pressure distributions at $t = 67.5$.

The reference model stays perfectly symmetric throughout the evolution. Its dynamical structure (left panels of Figs. 2 and 3) consists of the beam with several internal X-shaped shocks, ending abruptly at the terminal shock (Mach disk). The beam is surrounded by the low-density cocoon (light-gray area with an irregular border in the density plot) which, in turn, is embedded in the ambient medium swept by the bow shock (the latter is still visible in the upper part and bottom corners of the computational domain). Because of the density gradient in the ambient medium, the velocity of the bow shock and the expansion rate of the cocoon increase with increasing distance from the mid-plane of the disk, resulting in pear-like shape of the former and in a roughly conical shape of the latter.

For both models B and C the bending effect and its driving force, the pressure contrast, are clearly visible. In model B, due to the small scaleheight, the pressure gradient across the beam is so large that it causes the beam to decollimate rather than to bend (although the bending effect is also visible in the upper part of the plot).

A nearly ideal illustration of the expected effect is provided by model C. The beam is continuously deflected towards the disk axis, but the internal shocks can be easily identified as counterparts of the internal shocks in the reference model (right panel in Fig. 3). However, the Mach disk and the shocks above it are irregular, causing the hottest spot in the head of the jet to wobble about the beam (the wobbling is best visible in the computer generated movies accessible at http://www.camk.edu.pl/~tomek/RJET/index.html#modelC).

Discussion

Our preliminary results indicate that the proposed bending mechanism may indeed be efficient enough to cause observable deflections. According to theoretical estimates, the bending effect will be particularly strong in the case of light and moderately relativistic jets. This conclusion is confirmed by a broader survey of
the parameter space (to be reported in near future). Also, we note that the bending effect can be accompanied by beam decollimation if the density gradient in the ambient medium is too steep.

Since the time span of our simulations (few months) is rather small, we cannot be sure if any stationary or quasi-stationary deflections could be obtained, as
the expansion of the bow shock and the cocoon modifies the density and pressure distributions in the ambient medium. However, the rotation of the nuclear disk or torus (not accounted for in our 2D models) would restore the original distributions. We expect that the restoring effect would be stronger of the two, but this expectation can only be confirmed by fully 3D simulations including realistic disk models.

Also, since the cocoon pressure decreases as the cocoon expands, the net force acting on the jet tends to decrease with time. On the other hand, the ambient density contrast increases as the bow shock propagates sideways, tending to strengthen the bending mechanism. Another comment concerns the flows in the cocoon. In the slab jet simulations presented here, the two sides of the cocoon are disconnected, and pressure balance in the cocoon can only be reached by pushing the beam sideways. However, in the case of an initially cylindrical, three-dimensional jet, the flow of gas in the azimuthal direction (in the cocoon, around the beam), would tend to suppress the bending mechanism. All these effects should be included in future investigations.

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