Electromagnetic Models of Extragalactic Jets

M. Lisanti and R. Blandford

Physics Department, Stanford University, Stanford, CA 94305
Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305

Abstract. Relativistic jets may be confined by large-scale, anisotropic electromagnetic stresses that balance isotropic particle pressure and disordered magnetic field. A class of axisymmetric equilibrium jet models will be described and their radiative properties outlined under simple assumptions. The partition of the jet power between electromagnetic and mechanical forms and the comoving energy density between particles and magnetic field will be discussed. Current carrying jets may be recognized by their polarization patterns. Progress and prospects for measuring this using VLBI and GLAST observations will be summarized.

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INTRODUCTION

It is believed that relativistic astrophysical jets are formed by rotating magnetic fields around black holes and other accreting objects. As the jet accelerates away from the central production region, its Poynting flux is converted to kinetic energy flux. Models of steady-state ideal magnetohydrodynamic (MHD) flows predict that this conversion process is efficient up to a few light cylinder radii (Beskin et al. 1998). It is unclear, however, how the conversion proceeds beyond this point, where strongly nonlinear MHD differential equations challenge both analytical and numerical techniques (Sikora et al. 2005). Whether jets remain dominated by Poynting flux at large-scale distances remains an open question. Some have argued that a dominant magnetic component is necessary to accelerate electrons and positrons to speeds that can account for the observed synchrotron and X-ray emission from jets. However, this emission can also arise from other mechanisms, such as shocks and shears in the plasma flow.

Whether or not the Poynting flux is dominant far from the central source, it is plausible that the magnetic field of the jet becomes mainly toroidal at these distances. This follows from the fact that the poloidal and toroidal components fall off as $\propto d^{-2}$ and $\propto d^{-1}$, respectively (where d is the distance to the source). There has been some experimental evidence for toroidal fields in Faraday rotation measures of parsec-scale jets (Asada et al. 2002; Gabuzda et al. 2004), although cases exist where no Faraday rotation gradients were detected (Zavala & Taylor 2003). Improvements in resolution are needed before any firm conclusions can be drawn.

This work investigates a popular candidate model in which jets are confined by toroidal magnetic fields. The particle and electromagnetic contributions to the jet power are studied, and the consequent observable parameters of the emission spectrum are derived.

THE MODEL

This model only considers regions of jets that are far (much greater than ~ 100 Schwartzschild radii) from the central source. In this region, the jet is well-collimated and can be approximated as an axially and translationally symmetric fluid current $I(r)$ moving in the $\hat{z}$ direction with Lorentz factor $\Gamma(r)$. The coordinate r is the cylindrical radius of the jet. The internal pressure of the jet is $P(r)$, where $P(r) >> P_{ext}$, the ambient gas pressure. A return current is presumed to exist at some large r. The magnetic field only has a toroidal component B_ϕ and the expression for the current is

$$I(r) = \frac{2\pi r}{\mu_o}\Gamma(r)B_\phi(r) \tag{1}$$

Magnetohydrostatic equilibrium is obtained by balancing the forces due to the kinetic motion of the particles in the jet and the force density of the confining magnetic field. In equilibrium, the total force density must vanish, yielding

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the following expression for the mechanical pressure of the jet:

$$\frac{d}{dr}P(r) = \frac{\mu_o}{8\pi^2 r^2}\frac{d}{dr}\frac{I^2}{\Gamma^2} \tag{2}$$

The expression for the jet power is obtained from the energy-momentum tensor of the relativistic electron plasma. The kinetic and electromagnetic contributions are, respectively,

$$L_P = 8\pi c\int_0^R r\Gamma(\Gamma^2-1)^{1/2}P(r)dr \quad \text{and} \quad L_{EM} = \frac{Z_o}{2\pi}\int_0^R \frac{dr}{r}(1-\Gamma^{-2})^{1/2}I^2, \tag{3}$$

where $Z_o = c\mu_o$ is the characteristic impedance of free space.

The equations for the particle and electromagnetic power were evaluated numerically for ~ 20 different functional forms of $I(r)$ and $\Gamma(r)$. Typically, $L_P \sim (3-20)L_{EM}$ for $\Gamma(r=0) \sim 10$. It is actually not possible to find physical forms for the current and gamma functions that lead to Poynting-flux dominated jets in this magnetic-pinch model. One way to see this is to write L_{EM} in terms of the mechanical pressure $P(r)$:

$$L_{EM} \propto \int_0^1 dr\Big\{\Big[\frac{\Gamma}{r}(\Gamma^2-1)^{1/2}P(R)\Big] - \Big[r\Gamma(\Gamma^2-1)^{1/2} + 2r\int_0^r dr'\frac{\Gamma}{r'}\Gamma(\Gamma^2-1)^{1/2}\Big]P(r)\Big\}, \tag{4}$$

where R is the radius of the jet. Each set of square brackets contains a nonzero, positive function of $\Gamma(r)$. The electromagnetic power is maximized only when the mechanical pressure $P(r)$ is centrally concentrated (i.e., approaches a delta function as $r \rightarrow 0$), which is certainly not a realistic situation.

DISCUSSION

This work proposes a simple model that treats an extragalactic jet as an axially symmetric fluid current confined by a toroidal magnetic field. As discussed, the energy density of such jets is dominated by kinetic contributions, as opposed to Poynting flux.

It is possible to identify current-carrying jets experimentally by their polarization properties. In particular, the rotation measure can be calculated for particular distributions of the current. If one assumes that the jet is surrounded by a thermal plasma of electron density $n(r)$, then the rotation measure may be approximated as RM $\propto \langle n\rangle \int \mathbf{B}\cdot d\mathbf{s}$. Because the magnetic field is toroidal, the only contribution to the integral comes from the B-field along the boundary of the jet (r=R). Measurable rotation measures are expected:

$$RM = 5.2\times 10^4\left(\frac{I(R)}{EA}\right)\left(\frac{\langle n\rangle}{cm^{-3}}\right)\sin^{-1}\left(\frac{x}{R}\right) \quad \text{rad m}^{-2} \tag{5}$$

where x is the transverse distance of the jet on the sky.

It is also possible to predict the radiative properties of magnetically-pinched jets, such as the observed flux per unit length and the brightness temperature. A full analysis of this will be published elsewhere. Future work will focus on the stability and time-dependence of the dynamical model proposed here, as well as inertial effects, particle acceleration/cooling, and jet expansion. An analysis of inverse Compton scattering to gamma rays in such jets is also important, given the approaching launch of GLAST.

REFERENCES

Asada, K., Inoue, M., Uchida, Y., Kameno, S., Fujisawa, K., Iguchi, S., and Mutoh, M. 2002, PASJ, 54, L39
Beskin, V.S., Kuznetsova, I.V., & Rafikov, R. R. 1998, MNRAS, 299, 341
Gabuzda, D. C., Murray, E., & Cronin, P. 2004, MNRAS, 351, L89
Sikora, M., Begelman, M., Madejski, G., and Lasota, J. 2005, Ap J, 625, 72
Zavala, R. T. & Taylor, G. B. 2003, Ap J, 589, 126