Electromagnetic Models of Extragalactic Jets

Mariangela Lisanti and Roger Blandford
KIPAC, Stanford University

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 observations will be summarized.

Introduction

Jets are tightly collimated plasma flows that can travel at speeds close to the speed of light. First observed in 1918 emanating from the giant elliptical galaxy M87, jets have since been mapped out very well in the radio using VLA and VLBA measurements. They are now considered to be a common feature of compact accreting objects, such as active galactic nuclei, galactic x-ray transients, microquasars, and neutron star binaries. The most powerful extragalactic jets have radio powers greater than $10^{38}$ W and are typically 100-300 kpc in extent. The double radio sources can expand for several Mpc. The extragalactic jets have radio powers greater than $10^{38}$ W. The rotation measure, $\theta$, is a quantity that measures the line-of-sight path difference of left-hand and right-hand circularly polarized light, $\theta = \frac{\pi}{\lambda^2} \int B \cdot \vec{D} \, ds$, where $\lambda$ is the wavelength of the light, $B$ is the magnetic field, and $\vec{D}$ is the magnetic field vector.

Dynamical Model of Jet Confinement

Typically, equipartition pressure in jets exceeds the ambient gas pressure. However, jets do not appear to freely expand, so some other confining mechanism must exist. Confinement can result from the tension of the jet’s magnetic field lines. In a simple model, assume that the jet is an axially and translationally symmetric fluid current $I(r)$ moving in the $z$ direction with Lorentz factor $\Gamma(r)$. The internal pressure of the jet is $P(r)$, where $P >> P_{\text{mag}}$ and a return current is presumed to exist at some large cylindrical radius. The magnetic field is toroidal in the observer frame and the current is $I(r) = 2\pi \eta \Gamma B_z \Phi(r)$. Faraday rotation measurements provide evidence for toroidal fields.

Conclusions & Future Work

We propose a model that treats the jet as an axially symmetric fluid current confined by a toroidal magnetic field. Under a set of simple assumptions, the particle and electromagnetic contributions to the jet power were calculated for a variety of different current and gamma functions. It was found that, in most cases of experimental interest, the confined jet is dominated by the kinetic power. Presently, VLBI surveys of thousands of sources are underway. We have shown that it is possible to identify current carrying jets from their polarization and radiative properties. Future work will focus on the stability and time dependence of the dynamical model proposed here, as well as inertial, particle acceleration/collimation, and jet expansion. An analysis of inverse Compton scattering to gamma rays in such jets is also important, given the approaching launch of the Gamma-Ray Large Area Space Telescope (GLAST).

Acknowledgements: M.L. would like to acknowledge financial support from the NDSEG and the Stanford Humanities & Sciences fellowships.

Jet Power: Particle vs. EM

The particle and electromagnetic power were calculated for $\sim 20$ different functional forms of $I(r)$ and $\Gamma(r)$. Typically,

$$L_p \sim (3 - 20) L_{\text{EM}}, \quad \Gamma_o \sim 10$$

Variational techniques prove that $L_{\text{EM}} > L_p$ in cases when the mechanical pressure is centrally concentrated (i.e., approaches a delta function as $r \to 0$).

Faraday Rotation

Assume that the jet is surrounded by a thermal plasma of electron density $n_e$. The rotation measure, $\theta_{\text{rms}} \sim \frac{\theta}{\lambda^2} \int B \cdot \vec{D} \, ds$, is calculated along the Stokes circuit $\gamma_{\text{rms}}$, which is shown to the right. Because the $B$ field is toroidal, the only contribution to the integral comes from the loop along the boundary of the jet $n(r)$ of length $s$ on the sky. Measurable rotation measures are expected.

$$\theta_{\text{rms}} \approx 5 \times 10^{-5} \left( \frac{B_z}{\gamma} \right) \left( \frac{\lambda}{\mu m} \right) \text{mrad}^2 \text{mm}^{-3}$$

Emission Properties

In this model, the current and gamma function distributions are free parameters; by choosing expressions for $I(r)$ and $\Gamma(r)$, it is possible to predict the jet’s radiative properties. For instance, the observed flux per unit length for a jet oriented at $5^o$ to the l.o.s. is

$$F_r = 0.11 \left( \frac{\eta}{\gamma} \right)^{3/4} \left( \frac{\gamma_0}{\gamma} \right)^{-1/2} \int_0^{\gamma_0} \left( \frac{\Gamma \, \eta}{\gamma_0} \right)^{1/2} \, \frac{d\Gamma}{d\gamma} \, d\gamma$$

where $\eta$ is the angular distance from the jet center. For the example given in the box to the upper-right, the flux per unit length is

$$-0.11 \text{ mJy}\text{mas}^{-1} \text{ and the brightness temperature } T_r = T_{\text{b}} \Gamma(t) \text{ is shown to the left. (Note that } T_{\text{b}} \approx 1 \text{ TK.})$$

A similar analysis can be performed for other functional forms of the current and gamma functions.

Predictions of the Model