Electromagnetic Models of Extragalactic Jets

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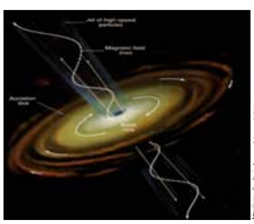
Abstract

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.

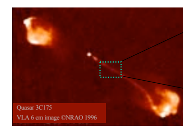
Introduction

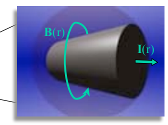
Jets are tightly collimated plasma flows that can travel at speeds close to the speed of light. First observed in 1918 emanating from the giant elliptical galaxy M87, jets have since been mapped out very well in the radio using VLA and VLBA measurements. They are now considered to be a common feature 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 radio spectrum is believed to result from synchrotron radiation from relativistic electrons trapped by the jet's magnetic fields. Inverse Compton scattering by electrons in the jet accounts for the gamma ray emission; x-rays are produced by either synchrotron or inverse Compton emission.



The three possible carriers of jet power are protons, electron-positron pairs and electromagnetic fields. It is unknown which of these carriers dominates in particular regions of the jet's length or by what mechanism the dominant carrier transforms as one moves further from the jet center. We investigate a popular candidate model for jet collimation in detail, paying close attention to particle and electromagnetic contributions to the jet power, and deriving the consequent observable parameters of the emission spectrum.

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 $P \gg P_{ext}$, 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 $I(r) = 2\pi r\, \Gamma\, B_\varphi/\mu_o$. Faraday rotation measurements provide evidence for toroidal fields.

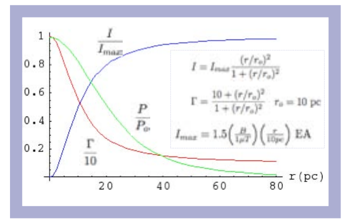
$$\frac{d}{dr}P(r) = -\frac{\mu_o}{8\pi^2 r^2}\frac{d}{dr}\frac{I^2}{\Gamma^2}$$

This is a statement of magnetohydrostatic equilibrium; the mechanical pressure force density of the jet $-\nabla P(r)$ is equal to its magnetic force density $\mathbf{J}\times\mathbf{B}$.

$$L_P = 8\pi c\int_0^R r\Gamma(\Gamma^2-1)^{1/2}P(r)dr \qquad L_{EM} = \frac{Z_o}{2\pi}\int_0^R \frac{dr}{r}(1-\Gamma^{-2})^{1/2}I^2$$

Expressions for the particle power L_P and electromagnetic power L_{EM} are shown above. The power dL is the energy flux density $cT^{o\alpha}$ through a differential area of the fluid surface. The energy flux density for a relativistic fluid flowing in the **z** direction is $Pc\,(1-\Gamma^{-2})^{1/2}\,\Gamma^2$, where P is the pressure.

An Example



The mechanical pressure P(r) is calculated from the stress balance equation; its maximum value is $P_o \sim 1.6 \times 10^{25}\,(I_{max}/EA)^2$ N m^{-2}. For a jet of radius $r \sim 100$ pc, $L_P / L_{EM} \sim 7$ and the total emitted power is $L = L_P + L_{EM} \sim 6.4 \times 10^{38}\,(I_{max}/EA)^2$ W.

Predictions of the Model

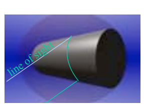
➢ Jet Power: Particle vs. EM

The particle and electromagnetic power were calculated for ~ 20 different functional forms of I(r) and Γ(r). Typically,

$$L_P \sim (3-20)L_{EM} \qquad \Gamma_o \sim 10$$

Variational techniques prove that $L_{EM} > L_P$ 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(r). The rotation measure, $RM \propto \langle n\rangle \int_C \mathbf{B}\cdot d\mathbf{s}$, is calculated along the Stokes circuit 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 (r=R) of length x on the sky. Measurable rotation measures are expected:

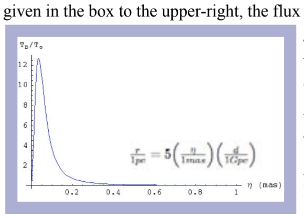
$$RM = 5.2\times10^4\left(\frac{I(R)}{EA}\right)\left(\frac{\langle n\rangle}{cm^{-3}}\right)\sin^{-1}\left(\frac{x}{R}\right)\quad \text{rad/m}^2$$

➢ Emission Properties

In this model, the current and gamma function distributions are free parameters; by choosing expressions for $I(r)=I_{max}f_I(r)$ 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° to the l.o.s. is

$$S_\nu = 0.11\left(\frac{I_{max}}{EA}\right)^{3/2}\left(\frac{\nu}{GHz}\right)^{-1/2}\left(\frac{d}{Gpc}\right)^{-1/2}\int d\eta\frac{\eta^{-3/2}f_I(\eta)^{3/2}}{\Gamma^4(1-\sqrt{1-\Gamma^{-2}})^{5/2}}\ \text{mJy mas}^{-1}$$

where η 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 mJy mas^{-1} and the brightness temperature $T_B = T_o\,T(\eta)$ is shown to the left. (Note that $T_o \sim 1$ TK.) For this current and gamma function, the jet is limb darkened.

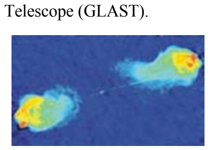


A similar analysis can be performed for other functional forms of the current and gamma functions.

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 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 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.