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Polarization and energy content of parsec-scale AGN jets

Maxim Lyutikov[1], Vladimir Pariev[2,3], Denise Gabuzda[4]

[1] University of British Columbia, Vancouver, Canada
[2] University of Wisconsin Madison, Madison, USA and
[3] Lebedev Physical Institute, Moscow, Russia
[4] University College Cork, Cork, Ireland

Abstract. Most of energy carried by relativistic AGN jets remains undetected until hundreds of kiloparsecs where interaction with intergalactic medium produces hot spots. The jet's hidden energy is only partially dissipated at smaller scales, from parsecs to kiloparsecs. Several media may play the role of the "prime mover": ions, pairs or large scale magnetic fields . Analyzing VLBI polarization structures of relativistic parsec scale jets we conclude that large-scale magnetic fields can explain the salient polarization properties of parsec-scale AGN jets. This implies that large-scale magnetic fields carry a non-negligible fraction of jet luminosity. We also discuss the possibility that relativistic AGN jets may be electromagnetically (Poynting flux) dominated. In this case, dissipation of the toroidal magnetic field (and not fluid shocks) may be responsible for particle acceleration.

Key words. galaxies: active – galaxies: jets – galaxies:

1. Introduction

It is generally accepted that AGN jets are produced (accelerated and collimated) by electromagnetic forces originating either near the central black hole (e.g. Blandford-Znajek mechanism, or ergosphere driving (Semenov et al. 2004)) or/and above the accretion disk (Lovelace et al. 1987). At present, full 3-D general relativistic MHD simulations are beginning to probe these mechanisms (Hirose et al. 2004; McKinney & Gammie 2004). The above simulations show formation of a magnetically-dominated funnel, roughly in agreement with theoretical predictions.

It is reasonable to expect that large scale fields remain in the jet as it propagates through ISM and IGM. Such field should then show through polarization properties of synchrotron emission. In contrast, polarization of parsec scale jets is commonly attributed to compression of *random* magnetic field at internal shocks. Motivated by this discrepancy we reconsidered polarization of optically thin synchrotron emission of parsec scale jets, trying to answer the question whether it can be produced by large scale fields (Lyutikov et al. 2004).

2. Polarization of relativistic sources

Conventionally (and erroneously for a relativistically moving plasma!), the direction of the observed polarization and the associated magnetic fields are assumed to be orthogonal to each other. This is incorrect procedure for relativistic AGN jets since relativistic boosting changes the relative strength of the magnetic field components along and orthogonal to the line of sight, which transform differently under the Lorentz boost, so that the strength of the jet poloidal and toroidal fields measured in the laboratory frame would be different from those measured in the jet frame. In addition, since the emission is boosted by the relativistic motion of the jet material, the polarization position angle rotates parallel to the plane containing the velocity vector of the emitting volume $\mathbf{v}$ and the unit vector in the direction to the observer $\mathbf{n}$, so that *the observed electric field of the wave* $\hat{\mathbf{e}}$ *is not, in general, orthogonal to the direction of unit vector along the observed magnetic field* $\hat{\mathbf{B}}$ (Blandford & Königl 1979; Lyutikov et al. 2003):

$$\hat{\mathbf{e}} = \frac{\mathbf{n}\times\mathbf{q}}{\sqrt{q^2-(\mathbf{n}\cdot\mathbf{q})^2}},$$
$$\mathbf{q} = \hat{\mathbf{B}} + \mathbf{n}\times(\mathbf{v}\times\hat{\mathbf{B}}). \quad (1)$$

The angle between observed electric field (unit vector $\hat{\mathbf{e}}$ and magnetic field is (Fig. 1)

$$\hat{\mathbf{e}}\cdot\hat{\mathbf{B}} = (\mathbf{v}\times\hat{\mathbf{B}})\cdot(\mathbf{n}\times\hat{\mathbf{e}}) \not\equiv 0 \quad (2)$$

(Similar relations can be written for polarization produced at oblique shocks by compression of random magnetic field .) Thus, to reconstruct the internal structure of relativistic jets from polarization observations, one needs to know both the polarization *and* the velocity field of the jet. Overall, plotting the direction of the electric field should be considered the only acceptable way to represent polarization data for sources where relativistic motion may be involved.

3. Polarization from unresolved cylindrical jet with helical magnetic field

Let's the (emissivity averaged) magnetic field in the jet rest frame (again properly averaged in the case of sheared jets) be defined by toroidal field B'_ϕ and poloidal field B'_z, so that the pitch angle ψ' *in the rest frame* is $\tan\psi' = B'_\phi/B'_z$. Note, that the pitch angle in the laboratory frame, $\tan\psi = \Gamma\tan\psi'$ is much larger. One should be careful in defining what is meant by, for example, a toroidally dominated jet. A strongly relativistic jet which is slightly dominated by the poloidal field in its rest frame, $B'_z \geq B'_\phi$ may be strongly toroidally dominated in the observer frame, $B_\phi \gg B_z$.

Qualitatively, in order for the jet polarization to be oriented along the jet axis, the intrinsic toroidal magnetic field (in the frame of the jet) should be of the order of or stronger than the intrinsic poloidal field (Fig. 1); in this case, the highly relativistic motion of the jet implies that, in the observer's frame, the jet is *strongly* dominated by the toroidal magnetic field $B_\phi/B_z \geq \Gamma$.

3.1. Comparison with observations: unresolved jets

Polarization properties expected from jets carrying large scale magnetic fields compare well with observations, being able to explain both the general trends as well as possible exceptions.

- The position angle of the electric vector of the linear polarization has a bimodal distribution, being oriented either parallel or perpendicular to the jet.
- If an ultra-relativistic jet with $\Gamma \gg 1$ which axis makes a small angle to the line of sight, $\theta \sim 1/\Gamma$, experiences a relatively small change in the direction of propagation, velocity or pitch angle of the magnetic fields, the polarization is likely to remain parallel or perpendicular; on the other hand, in some cases, the degree of polarization can exhibit large variations and the polarization position angle can experience abrupt 90° changes. This change is more likely to occur in jets with flatter spectra.
- For mildly relativistic jets, when a counter jet can be seen, the polarization of the counter jet is preferentially orthogonal to the axis, unless the jet is strongly dominated by the toroidal magnetic field in its rest frame.

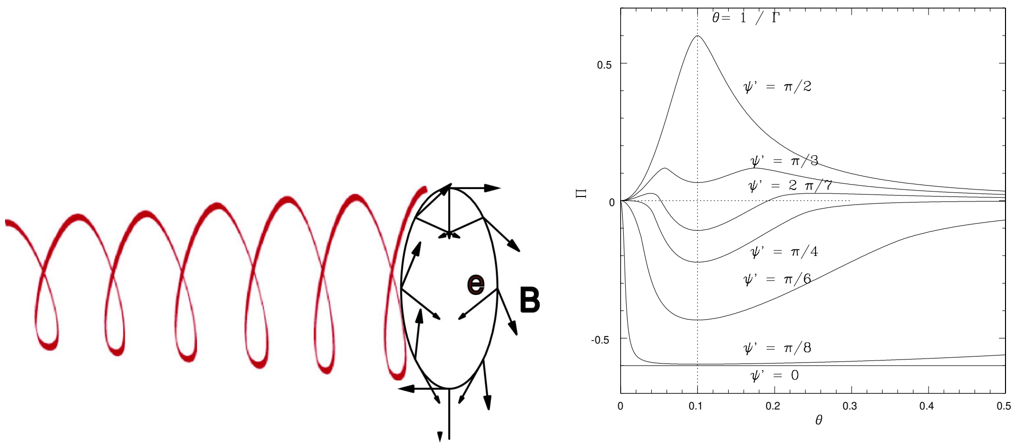

Fig. 1. (a) Example of observed electric field in the wave and magnetic field for helical field with $\psi' = \pi/4$, $\Gamma = 2$, $\theta_{ob} = \pi/3$.(b) Polarization fraction for unresolved cylindrical shell as a function of the observer angle θ for $p = 1$, $\Gamma = 10$ as a function of the pitch angle ψ'. Positive values indicate polarization along the jet, negative — polarization orthogonally to the jet.

3.2. Resolved jets

To find the total emission from a resolved jet one must know the distribution of the emissivity and the internal structure of the jet, both of which are highly uncertain functions. We have considered a number of force-free jet equilibria with different prescriptions for emissivities. We conclude that

- In "cylindrical shell" type jets (when emissivity is concentrated at finite radii away from the axis), the central parts of the jet are polarized along the axis, while the outer parts are polarized orthogonal to it.
- Contrary to the above, a quasi-homogeneous emissivity distribution cannot reproduce the variety of position angle behavior observed, since average polarization remains primarily orthogonal to the jet, dominated by the central parts of the jet where the magnetic field in the co-moving frame is primarily poloidal (since the toroidal field must vanish on the axis).

3.2.1. Spin of the central object

Polarization observations of resolved jets can be used to infer the relative orientation of the spin of the central object that launched the jet (black hole or disk): whether it is aligned or counter-aligned with the jet axis. This possibility comes form the fact that the *left and right-handed helices produce different polarization signatures,* see Figs. 2. In order to make a distinction between the two choices, it is necessary to determine independently the angle at which the jet is viewed in its rest frame, which for relativistic jets amounts to determining the product $\theta\Gamma$: if $\theta\Gamma < 1$ then the jet is viewed "head-on," while the jet is viewed "tail-on" if $\theta\Gamma > 1$.

4. Conclusion

Our calculations indicate that large-scale magnetic fields may be responsible for the polarization observed in parsec-scale jets in AGNs. In order to produce the substantial degrees of polarization that are observed in these jets, the total energy density of the ordered component of the magnetic field must be at least comparable to the random component. Unless the random component is been constantly regenerated, large scale toroidal field will dominate over random field as the jet expands. On the other hand, for conically expanding, constant

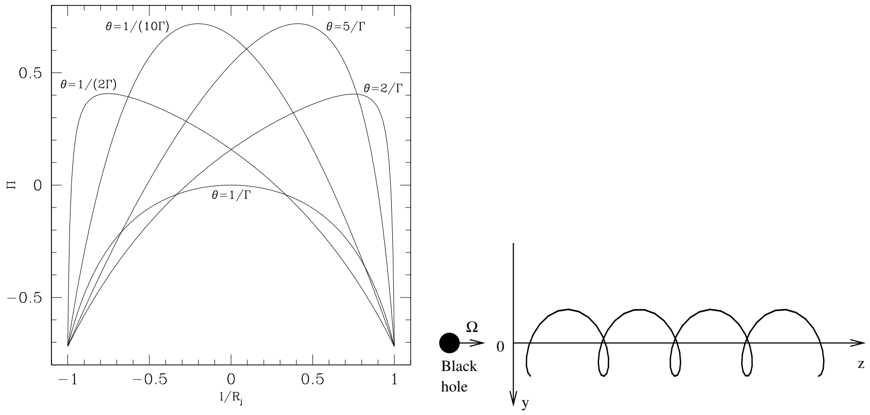

Fig. 2. (a) Profiles of the polarization degree Π for resolved cylindrical shells as a function of the distance across the jet for $\Gamma = 10$, $p = 2.4$, $\psi' = 45^0$. (b) A "head-on" ($\theta\Gamma < 1$) view of a left-handed helical magnetic field in the reference frame co-moving with the jet in the positive z-direction. Polarization Π of the lower, $y > 0$, part is larger, i.e. it is more likely to be along the jet.

Lorentz factor jet the rest mass energy density falls off with radius similarly to toroidal magnetic field energy density , $\rho c^2, B_\phi^2 \propto r^{-2}$, so that their ratio, $\sigma = B^2/(8\pi\Gamma\rho c^2)$ remains constant.

Detectable presence of large scale magnetic field implies that σ is not too small, $\sigma \geq 1$. A possibility, which remains to be proven, is that $\sigma \gg 1$ in the bulk of the jets, so that energy is transported along the jets mainly in the form of the Poynting flux up to very large distances. In this case dissipation of magnetic energy, and not fluid shocks, are responsible for particle acceleration (Blandford 2002; Pariev et al. 2003).

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