CURRENT SYSTEMS IN RADIO JETS

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The structure of the magnetic field in radio jets is a topic of recent interest, especially due to the possibility that some high pressure jets are confined by a magnetic pinch. Several such jets have been found which cannot be confined by external cluster gas pressure, on which there are observational limits; nor can they be in free expansion, since they do not show evidence of adiabatic expansion losses. Recent radio interferometer observations of surface brightness and polarization allow the possibility of determining the magnetic field structure. In this paper I present some basic considerations of the current and field structure required if the observed jets are to be magnetically confined.

BASIC MAGNETIC CONFINEMENT

The simplest MHD equilibrium in a cylindrical geometry is the classic Bennett pinch, in which the tension of an azimuthal field, B_ϕ, balances the plasma pressure. The field, pressure and axial current are related by

$$B_\phi^2 \sim 8\pi p \; ; \qquad j_z = cB_\phi/2\pi r \; ; \tag{1}$$

if r is the jet radius. For radio jets with $p \gtrsim p_{eq} \sim 10^{-10}$ dyn cm^{-2} (note that equipartition estimates are lower limits for the internal pressure), $B_\phi \sim B_{eq} \sim 10$ to 100 μG is needed, hence a current density $j_z \sim 10^{-16}$ cgs. The net current is $I = \pi r^2 j_z \sim 10^{18}$ A. If this current were to arise from a charge imbalance in the streaming plasma, one extra electron in $\sim 10^{12}$ particles would be required. This small imbalance nonetheless would lead to a charge accumulated in the end of the jet or the radio lobes which would be large enough to stop the jet (which is carrying $\rho v_j^2 \pi r^2$ of kinetic energy) in only 10 to 10^3 years. Thus, a complete circuit must exist.

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Very little can be said about the path of the return current. The observations discussed below do not admit solutions in which the return current lies on the jet surface. Alternative possibilities may be on the boundary layer between a "cocoon" of the radio source and the cluster gas (Benford, 1978), or an even more diffuse (field aligned?) current in the cluster gas itself. The former would be akin to, say, magnetopause currents driven by the solar wind dynamo. The latter would require a cluster field with the right configuration; very few observational constraints have yet been put on any such field.

THE NATURE OF JET FIELDS AND CURRENTS

At least two separate lines of argument suggest that the jet field has a flux rope-like structure. Near the axis the field must be mostly longitudinal (pitch angle $\to 0$), and away from the axis the field must become mostly azimuthal (pitch angle $\to \pi/2$). The radio luminous plasma must lie mostly in the region where B_z dominates; the B_ϕ region must be lacking in luminous plasma, and is probably nearly force-free. The arguments for this structure are as follows:

(a) This structure is consistent with observations, which often show a projected field parallel to the jet in luminous (high energy density) cases (Bridle, 1982), and yet it can provide the magnetic confinement through the external B_ϕ. (Note, however, that some small amount of B_ϕ in the luminous plasma will still produce a projected parallel field; Laing, 1981).

(b) Calculations of static cylindrical magnetic pinches suggest that this type of configuration may be more stable than the pure theta pinch, which is notoriously unstable to pinching and twisting modes (e.g., Goedblod, 1971; Cohn, 1983).

Of course the MHD equilibrium condition,

$$\nabla p + \frac{\bar{j}}{c} \times \bar{B} = 0 \; , \qquad \bar{j} = \frac{c}{4\pi} \nabla \times \bar{B} \; , \tag{2}$$

admits many solutions satisfying these general conditions, with boundary conditions p, B_z = finite as $r \to 0$; p, B_z, $B_\phi \to 0$ as $r \to \infty$. Typical choices of solutions are shown in Figure 1; more detailed calculations of field and current structure and integrated surface brightness will be presented elsewhere (Eilek, 1984).

ENERGETIC AND DYNAMO CONSIDERATIONS

One basic problem is "what drives the current?" One can address this problem by considering the energy budget of the jet flow, and by looking at general dynamo physics, with hopes of restricting the set of allowed models to less than all of parameter space.

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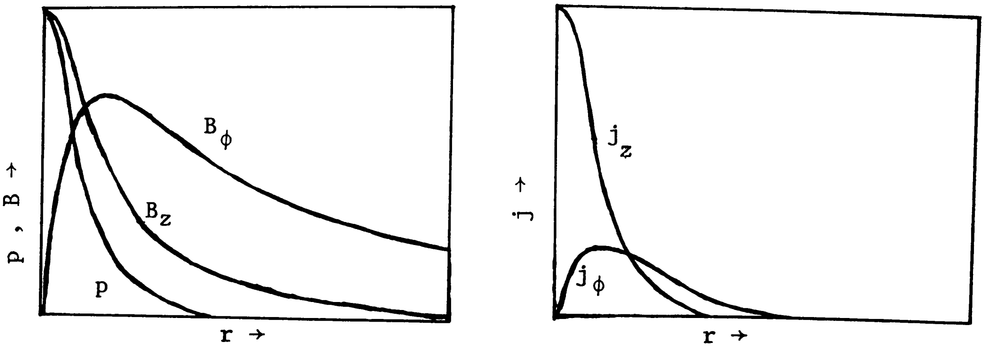

Figure 1. Behavior of p(r), B(r) and j(r) in typical equilibrium.

The size of the voltage drop and local dissipation associated with the confining current are important quantities. Both depend on the plasma conductivity, σ, which is of course hard to say anything about. Anomalous effects can lower the conductivity by several orders of magnitude over the traditional Lorentz gas value (which relies on electron-ion collisions to regulate the transport), due to higher collision rates in the presence of microturbulence. It turns out, however, that in radio sources even the most extreme estimate of the anomalous conductivity (when the collision rate is taken equal to the electron plasma frequency) still results in quite small voltages ($\Delta V \propto \sigma^{-1} \int \underline{j} \cdot d\underline{l} \sim 3 \times 10^6$ volts over a 10 kpc jet) and local ohmic losses ($j^2 \sigma^{-1} L << \rho_j v_j^3$, where the latter is the conventional estimate of local energy source in a jet flow). In the Lorentz gas limit, $\sigma \to \infty$ and both the voltage drop and the local dissipation are negligible.

Another important consideration is the nature of the battery or dynamo which drives the current. Two possibilities arise.

One model would attribute the dynamo to the "engine" in the galactic nucleus. This unspecified machine is also the source of the jet flow. Blandford (1976) and Lovelace (1976) have considered rotating compact objects as electromagnetic dynamos, and they estimate central electric potentials from objects which are well above that needed for the confining current. Application of such models to radio jets leads to the standard problem of coupling nuclear models (involving scales $\lesssim 1$ pc) to the extended structure (scales $\sim 10^3$ to 10^6 pc); in particular, in this case the question of how the current path is determined must be addressed. This area deserves further work.

An alternative model would use the jet itself to provide the dynamo. Since the kinetic energy flux in the jet, $\rho_j v_j^3$, is generally thought to be the local source of radiation and heat (through MHD/plasma turbulence generated in the jet and local particle reacceleration processes), it may be that this turbulent energy conversion can also supply an in situ kinematic dynamo. It is well established that fluid turbulence with non-zero helicity ($\overline{v} \cdot \nabla \times \overline{v} \neq 0$) can generate a net EMF and large scale magnetic field (e.g., Steenbeck, Krause and

Rädler, 1966; De Young, 1980). It may be that turbulence which develops in a jet which has an initial azimuthal velocity field could supply a local magnetic field with the proper configuration; specific calculations are required to address the dynamo problem in this context, and this author is not aware of any such work to date.

Energetic arguments, however, may indicate the limits of applicability of this idea, as follows. The best, "maximal helicity", case of turbulent generation of fields reaches a limit of rough equipartition, $B^2/8\pi \sim \rho_j v_t^2$, between the large scale fields and the turbulent energy density (De Young, 1980). But the MHD equilibrium requires $B^2/8\pi \sim p$. The turbulent velocity $v_t < v_j$, as generation of turbulence tends to be inefficient. Thus, this model may work only if $\rho_j v_t^2 \sim p < \rho_j v_j^2$, that is, for "lukewarm" jets. Some jets observed may satisfy this condition at present; but the inefficiency of turbulent field generation (much of the energy input goes into dissipation and plasma heating) may make it hard to maintain the $B^2/8\pi \sim p$ balance over the source lifetime.

OBSERVABILITY

The flux rope models above clearly can satisfy the general observational constraints, both in terms of surface brightness and projected field. It may be possible to discriminate between transverse profiles from the rate at which the surface brightness falls off, using well-resolved sources. The azimuthal confining field is harder to test, as by assumption it lies outside of the luminous plasma. It may be marginally detectable as a foreground Faraday screen, if the jet lies in a sufficiently dense ionized cluster gas. The rotation measure ($\chi \propto \int n_{ICM} B_\phi \cdot ds$) should vary systematically across the jet, as $B_\phi \cdot ds$ changes sign, and may be just large enough to be detectable.

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DISCUSSION

Sturrock: I do not see how a jet can generate the B_ϕ magnetic field in the surrounding intergalactic medium, since it has virtually infinite conductivity.

Benford: The return currents are necessarily set up by the electric field E_z induced by penetration of the jet head, which carries an increasing current. This field is spread over several jet radii, and probably even more, considering that E_z is made at the hot spot working surface, which is wider than the inner jet.

Vasyliunas: To make a flux rope, you have to twist at one end and hold it (or twist differently) at the other end. One end can be anchored in the central object, but what holds the other end, to twist the jet rather than have it simply rotating with the central object?

Eilek: If the jets are indeed flux ropes, perhaps the "working surface" when the jet hits the external plasma provides the anchor.

Coppi: Can you estimate, roughly, what the gross stability of the magnetic configuration may be?

Eilek: One can, of course, estimate stability to first order by anology with static pinches; but specific calculations which address the instability growth rates (in time and space) of jet flows in cluster environments are needed.

Elphic: A lesson from the Venus flux ropes: The return current you are worrying about is very diffuse in this case. It is distributed over a much larger area than the intense central axial current. In your situation the return current may be very tough to observe.

Guillory: If you could see the return current, you could probably estimate the age of the structure, since the field must penetrate the conducting plasma surrounding the jet.

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