IS THE JET IN M87 MAGNETICALLY CONFINED?

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Abstract: Calculations of the minimum pressure in the M87 jet show that the jet pressure is an order of magnitude in excess of the thermal pressure in the interstellar medium calculated from the X-ray emission. The continuous energy input required to produce the jet emission is incompatible with a freely expanding jet. On the other hand, the uniform jet expansion, the jet emission and the jet polarization can be explained if the jet is self-confined by j x B forces.

There are now several jets in which the minimum jet pressure appears to exceed the thermal pressure of the surrounding medium. One of these jets is associated with the quasar 4C32.69 (Potash and Wardle 1980). Other jets associated with extragalactic radio sources may also have minimum jet pressures that exceed the pressure in the surrounding medium (Burns et al. 1983). Calculations of the minimum jet pressure in the M87 jet have been made by Biretta et al. (1983). The pressure of the surrounding medium calculated from the X-ray data combined with a model of the cooling accretion flow in M87 decreases with distance from the nucleus with $P \propto z^{-1.5}$ (Lea et al. 1982) and is as much as an order of magnitude lower than the minimum jet pressure interior to Knot A. Static pressure confinement is not ruled out interior to Knot D. Only if this jet were extremely relativistic, $\gamma > 50$, could the jet be statically pressure confined. In part, this is because the relativistic jet must lie near the line of sight and the jet extends further outwards from the nucleus where pressures in the external medium are lower. The observations also show that the jet expands at a constant rate with opening angle $\sim$ 5 degrees at least to Knot A, that the polarized emission at 2 cm is somewhat limb brightened with the electric vector oriented perpendicular to the jet axis and that the radio brightness falls very slowly along the jet and the jet is nearly isothermal.

The constant opening angle of the jet could be produce by a freely expanding jet with initial Mach number of about 25. With no energy input such a jet must expand adiabatically. Energy input into a jet will be the result of dissipation of turbulence in the jet fluid. Turbulence

M. R. Kundu and G. D. Holman (eds.), Unstable Current Systems and Plasma Instabilities in Astrophysics, 439–443.

https://doi.org/10.1017/S0074180900075926 Published online by Cambridge University Press

is generated at the jet external medium interface and may be produced in the jet near the origin. In the free jet turbulence produced at the interface is restricted to a thin surface layer because jet expansion is more rapid than the internal sound speed. Ordering of the magnetic field in the jet prevents relativistic particle diffusion into the jet interior (Eilek 1982) and only a limb brightened configuration is produced. Turbulence in the interior can be produced at the origin of the jet but turbulent velocities decay and the fundamental eddy size increases as $\Delta u = \Delta u_o(t_o/t)^{5/7}$ and $l = l_o(t/t_o)^{2/7}$, respectively, with result that the energy dissipation rate per unit volume $\dot{E} \sim \rho\Delta u^3/l$ decreases rapidly as (Landau and Lifschitz 1959)

$$\dot{E} \sim \rho_o \Delta u_o^3 (z_o/z)^{31/7}/l_o$$

where $z = v_z t$, v_z is the jet velocity and ρ_o, Δu_o and l_o are the initial density, turbulent velocity and initial eddy size ($l_o \sim$ jet radius), respectively. Thus the requirement that there be approximately constant energy input into the M87 jet along the jet cannot be met if the jet is free. On the other hand, confinement of the M87 jet allows for continuous energy input throughout the jet through dissipation of turbulence generated at the jet boundary (Hardee 1983) which can keep the jet nearly isothermal (Begelman 1981).

Although the M87 jet cannot be confined by pressure of the external medium except perhaps interior to Knot D, the jet can be self-confined by j x B forces. If the jet velocity v_z remains nearly constant, the steady state dynamics of the magnetically confined jet in the radial direction provided the expansion is slow is given by (Chan and Henriksen 1980)

$$dv_r/dz = 2\ [P_j + B_z^2/8\pi - B_\phi^2/2n\pi]/\rho R v_z$$

where P_j is the internal thermal pressure at the jet axis, B_z is the component of the magnetic field parallel to the jet axis (here assumed constant across the jet) and B_ϕ is the strength of the confining magnetic field at the jet surface and n = 2 or 4 if the current is uniformly distributed across the jet or is a surface current, respectively. Note that $B_z^2 \propto R^{-4}$, $B_\phi^2 \propto R^{-2}$ and the $P_j \propto R^{-2}$ if the jet is isothermal. Thus, jet expansion will remain nearly constant if $P_j \sim B_\phi^2/2n\pi$. We must assume that pressure balance is established somewhere near the jet origin. Such a result might be produced by a hydromagnetic flow from an accretion disk (Blandford and Payne 1982).

The polarization observations provide a clue as to the nature of the current and orientation of the jet if it is magnetically confined. For a Faraday thin jet and helical magnetic field we can use the results obtained by Laing (1981) which describe the polarization properties of a cylindrical jet. We find that the polarization at jet center, the mild polarization limb brightening and the position angle of the electric vectors at 2 cm imply that the jet is oriented within 30 degrees of the plane of the sky and that at the jet surface the field helicity is less than 45 degrees, i.e., $B_\phi < B_z$ at the jet surface. The fact that B_ϕ should increase rapidly along the jet relative to B_z as the jet expands may be taken to imply that B_ϕ inside the jet must be restricted to a surface layer. If the conductivity of the material is high near the jet axis but decreased near the jet surface, perhaps because of increased turbulence, a self-consistent picture of the magnetic field emerges. Current flows are near the surface and the magnetic field is frozen into the fluid in the jet interior parallel to the flow. If the fluid carries angular momentum we expect small B_ϕ in the jet interior with B_ϕ increasing rapidly near the jet surface. The jet can be thought of as confined by the field that is outside the jet which is produced by a surface current. This configuration reproduces both the position angles of the electric vectors perpendicular to the jet axis and the modest limb brightening in the polarized intensity.

Finally we need to address the stability of this magnetically confined configuration. A magnetically confined jet will be sufficiently stable to pinching if the jet Mach number, M, is greater than about 3 (Cohn 1983), i.e., the rate of growth is too slow to affect the jet dynamics unless the jet is very long. This result is similar to that obtained for a jet that is thermally confined. An estimate of the minimum M87 jet luminosity when combined with an estimate of the jet's sound speed implies that $M > 3$ for the M87 jet and it is clear from the observations that the knots are not pinches in the flow. In general, the stability properties of a supersonic and superalfvenic hydromagnetic flow confined by $j \times B$ forces will be similar to the thermally confined case. The reason for the similarity is that the energy in such a system resides in the fluid flow and not in the magnetic fields and associated currents. Thus, results obtained for thermally confined jets (see the review by Ferrari) may be applied to magnetically confined jets. Some allowance must be made for the effects which result because the external magnetic field ties the external medium to the jet. This increases the jet's inertia. For example, this slows the growth of jet helicity (Benford 1981) and a supersonic flow with $M > 5$ will be sufficiently stable to helical twisting which will not affect the dynamics significantly. The fact that the M87 jet exhibits significant helicity downstream of Knot A implies different jet conditions in the inner and outer portions of the jet. Jets are also unstable to fluting wave modes which are harmonics of the helical wave mode. The fluting wave modes grow rapidly at wavelengths less than the jet radius. Short wavelengths can be suppressed by velocity shear (Ray 1982) but at least a few fluting wave modes with characteristic wavelength less than the jet radius will be sufficiently unstable to drive jet turbulence (Hardee 1983) and provide the heating and particle acceleration needed in the jet in M87.

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DISCUSSION

Henriksen: I have two comments: 1. Large scale magnetic fields are not inconsistent with turbulent jets. Both the velocity spectrum and the magnetic field spectrum can have large scale components. 2. If $\beta \propto R^{-2}$, then $p \simeq \rho v_t^2 \propto R^{-2}$.

Hardee: Particularly if turbulence in subsonic is a supersonic flow the magnetic fields will appear relatively well ordered in this observer' reference frame.

Uchida: Shibata and myself have done a calculation very much related to this model by Dr. Hardee and that by Dr. Eilek. A large difference is that ours deals with the transient process in which the B_ϕ produced by rotating motion in a $\beta >> 1$ region relaxes into the $\beta << 1$ region, and in this dynamical process the front of the relaxing packet of B_ϕ carries the material with it.

Hardee: At least approximately this is how I imagine that the jet becomes self-confined.

Bratenahl: Is there, within observational constraints, a more or less uniform B-field in space through which the jet passes? If so, is the strength $\sim$ microgauss? I am excited about this -- at UC Riverside we are trying to understand the mechanism by which our plasma jet penetrates the external field by polarization currents at the front.

Hardee: Yes, $\sim$ microgauss. This compares to a jet magnetic field of several hundred microgauss.

T. Ray: Could the known presence of the observed Hα filaments near the M87 jet give you any handle on the extent of the B_ϕ fields? (My reasoning being that if the Hα filaments where inside the B_ϕ field it would exert pressure on them).

Hardee: The B_ϕ field will fall off rapidly as 1/r outside the jet and may be screened by return currents.

Wilson: I wonder how confident you are about ruling out thermal confinement. The minimum internal jet pressure (magnetic and cosmic ray) is subject to the usual uncertainties, such as the exact geometric configuration of the field and particles, and the X-ray measurements of the external density refer to only a certain range of gas temperature. In such terms, a factor of 10 difference between the pressures may not be insurmountable.

Hardee: I am confident that the computation of the minimum jet pressure is accurate and is a firm lower limit. I am less certain about the X-ray data, but two separate computations using different assumptions arrive at estimates of the pressure in the external medium that differ by only a factor of 2 at 2 kpc from the nucleus. It is difficult to imagine any assumptions that could increase the external pressure by an order of magnitude.

Sturrock: What is your interpretation of what is happening at the knots?

Hardee: Pinching of the jet can be ruled out as a means of producing the knots. Aside from knot A, which is almost certainly a shock, I like the idea of turbulent bursts in the jet material as discussed by Henriksen.