ENERGY TRANSPORT IN RADIO SOURCES

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Dr. Pacini has dealt with the innermost parsec; my job is to comment on the next 999,999. I have four comments.

1. A reminder of the importance of using the bulk kinetic energy of whatever beam or jet there is - forms of energy that exert pressure will get lost on the way out because of adiabatic expansion (Longair et al. 1973).

2. What is the asymmetry of jets trying to tell us?
The classical double structure of radio sources is generally fairly symmetrical, showing us that these structures must have speeds <<c (Scheuer 1967, Mackay 1973, Longair et al. 1979). Most of the powerful radio sources (Class II of Fanaroff & Riley 1974) show no trace of the theoretically postulated energetic jets. In those cases where we do see jet-like features, they are one-sided: there are large scale jets in 3C219 (Turland 1975), NGC6251 (Waggett et al. 1977, Blandford et al. 1978) and the quasar 2349+32 (Potash & Wardle 1977) and there may be many cases like the VLBI-scale jet in the central source of 3C111, recently mapped by the Caltech group. (There are also jet-like features which are two-sided. but so far they have been observed *only* in sources of low radio luminosity, Fanaroff & Riley's Class I, which are morphologically quite different: sources like 3C31, 3C66B, etc. and radio "trail" sources such as 3C129 and NGC1265).

Is this one-sidedness of "jets" a real feature of the ejection mechanism, or is there an ejection of a pair of relativistic jets in opposite directions, of which we see only the more nearly approaching one? Double radio sources in a sample selected at a low frequency are clearly selected without bias in orientation, so that half of them should have their jets within 30° of the plane of the sky, but even at moderate inclinations the fluxes of approaching and receding jets can differ by an order of magnitude; furthermore, the selection effects tend to prevent the observation of jets close to the plane of the sky. The present statistical sample of jets within powerful double sources

Patrick A. Wayman (ed.), Highlights of Astronomy, Vol. 5, 667–669.

is tiny; we need observations of a larger sample, and observations with a large dynamic range, to settle this question convincingly.

3. Stability

If one takes the jet picture fairly literally, one must worry seriously about the possible dispersal of the jet caused by the growth of waves on the surface of the jet - instabilities of the Kelvin-Helmholtz type. It is true that modes transverse to the flow direction become stable (in the linear regime) when the flow is supersonic (Miles, 1958), but for sufficiently oblique modes the wave pattern moves over each fluid subsonically so that these modes still grow. Making the flow relativistic does not change this situation qualitatively (Blandford & Pringle, 1976, Turland & Scheuer, 1976); correspondingly, for a relativistic cylindrical jet, helical modes grow at any flow speed (Ferrari et al., 1978; Hardee, 1979) plus some additional pinching modes. I mention these details to explain why there has been so little real progress in this field: - 2D computer simulations almost inevitably represent only axisymmetric flows, and automatically suppress helical modes. There are many unsolved problems, for example the effects of the very high temperature - and therefore pressure - of any mixing layer that forms, when the Mach number is large. Many of the difficulties are alleviated if the jet is much denser than its surroundings (like the jet of water from a garden hose), for the growth rates are smaller and we can expect the entrained fluid and associated disturbances to be convected out along the jet. The notion of a heavy or 'free' jet is perhaps plausible at kpc distances from the nucleus, but close to the nucleus one must expect a rapidly increasing ambient gas density, and I should expect the jet to be a 'light' jet rising through a denser fluid. There is a way of stabilizing rapidly rising streams of light fluid when the ambient fluid has some rotation; the rising stream grows a vortex around itself, and in some sense the Kelvin-Helmholtz instability is overcome by a Rayleigh-Taylor stability due to the centrifugal "g". I do not understand the relevant physics well enough to know whether it is applicable to radio sources, but such streams certainly can be remarkably narrow and remarkably stable in nature; photographs of tornadoes serve to illustrate that statement.

4. Polarization

In *weak* radio galaxies (3C 31, 3C 449, 3C 296, ...) radio polarization measurements (extrapolated to zero wavelength) indicate that the magnetic field is not dragged out along the jet - as one might expect if there were slight interaction at the boundary - but, contrariwise, lies preferentially transverse to the jets. The measured sample is small, but so far it is very consistent for the 3C 31-type sources, and I think it is trying to tell us something. (The jet of M 87 (Schmidt et al., 1978) and the jet of 3C 219 do not follow this pattern). Maybe there is a current along the jet (e.g. Benford, 1978); another possibility is that we have a 'heavy' or 'free' jet again.

A 'free' jet, if moving at constant longitudinal velocity, expands sideways but not longitudinally; thus $B_{\parallel} \propto r^{-2} \propto R^{-2}$ while

$B_\perp \propto r^{-1} \propto R^{-1}$, where r is the radius of the jet, R is the distance from the nucleus, and we have assumed that the opening angle of the jet is constant. This readily explains the preferred transverse orientation of B, but, following the standard calculations of synchrotron radiation theory, leads to a radio power (W Hz^{-1} per kpc of length) proportional to $R^{-(1+7\alpha/3)}$ (where α is spectral index in the sense $S \propto \lambda^{\alpha}$) i.e. roughly $\propto R^{-3}$, whereas the observations show little if any regular decrease of power per kpc with distance along the jet, until the jet breaks up. Pure lateral expansion would also lead to a much greater fractional polarization than is observed. Blandford et al. (1978) indicated one fairly natural modification which uses only the kinetic energy of lateral expansion to supplement the fast particle energy, and thus does not contradict the postulate of a 'free' jet. A tangled field made very strongly anisotropic by lateral stretching will make itself less anisotropic by field line reconnection. Suppose that reconnection occurs at a rate that keeps the degree of anisotropy fixed, and converts the magnetic energy lost into fast particle energy. Then magnetic energy density $\propto R^{-2}$, fast particle energy density is a fixed fraction of this and thus also $\propto R^{-2}$, and the usual minimum energy formula then shows that radio power Hz^{-1} kpc^{-1} is proportional to $r^2(u_{min})^{7/4} \propto R^2(R^{-2})^{7/4} \propto R^{-3/2}$. That dependence is an advance on R^{-3} but I think it is still too fast to be in satisfactory agreement with observation.

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https://doi.org/10.1017/S1539299600004573 Published online by Cambridge University Press