LARGE-SCALE RADIO JETS

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The purpose of this review is to outline the systematic properties of radio jets on kpc scales, as derived from the basic observations of surface brightness and linear polarization and to emphasize the uncertainties in the determination of their physical parameters. These results come primarily from observations of about 100 jets with the VLA: a fuller account is given by Bridle (1982) and the proceedings of IAU Symposium 97 contain many illustrations and references, which must be omitted here.

I take a "jet" to be a feature in the radio brightness distribution which is at least four times as long as it is wide, which can be clearly separated (spatially or by brightness contrast) from the rest of the source and points away from a radio core. Wilson (1982) has considered jets in spiral galaxies and I shall discuss only the more luminous jets found in elliptical radio galaxies and quasars.

There are two classes of source in which jets are frequently detected: low-luminosity radio galaxies ($P \simeq 10^{22} - 5 \times 10^{24}$ W Hz^{-1} at 1400 MHz, with $H_o = 100$ km s^{-1} Mpc^{-1}) and extended quasars. Between 50 and 80% of the former type show prominent jets, which emit between 5 and 50% of their total flux. Similar percentages are found for the 3CR quasars, but jets are far less common in luminous galaxies ($P > 10^{26}$W Hz^{-1}). This is not to say that jets do not occur in powerful radio galaxies, but merely that they are very much weaker than the outer lobes.

Synchrotron radiation from jets is usually highly polarized (10 - 60%) and multifrequency polarimetry allows us to determine the projected magnetic field distribution. As a first approximation, we can distinguish two classes, according to the field direction on the jet axis: longitudinal (B_ℓ) and transverse (B_t). The field configuration may change along the jet, from being longitudinal close to the nucleus to transverse further out. The fraction of a jet over which the field is longitudinal is highly correlated with the luminosity of the core, being $\lesssim$ 20% for $P_{core} \lesssim 10^{23}$ W Hz^{-1} at 6 cm, and 100% for $P_{core} \gtrsim 10^{23}$ W Hz^{-1} in most

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cases. Some jets have B_ℓ at the centre and B_t at the edges (e.g. NGC 6251 Bridle 1982). There are exceptions to the evolution from B_ℓ to B_t, an example being M87 (Owen, Biretta & Hardee, in preparation), where the field is longitudinal in the inner regions, flipping to transverse at what appears to be a shock in the brightest knot and then becoming longitudinal again. The qualitative picture is that several processes act to determine the field pattern: a velocity gradient across the jet (leading to B_ℓ) and lateral expansion or longitudinal compression (e.g. due to deceleration or shocks), producing B_t.

Some low-luminosity sources (e.g. 1321+321; Ekers 1982) have two-sided jets with remarkably symmetrical brightness distributions. At the other extreme, some jets are very asymmetric, with jet-countejet ratios in excess of 50:1. There is a clear separation between B_ℓ and B_t - dominated regions, as follows: The B_ℓ jets cover a large range of side-to-side intensity ratios (usually > 4:1). Some of these have detected optical and X-ray emission. The B_t jets are usually fairly symmetrical with intensity ratios typically < 4:1. The B_t jets in low luminosity galaxies have B_ℓ bases, which are usually, but not always, one-sided.

For several well resolved B_t jets the variations of transverse width, R, with distance from the nucleus, z, have been measured (Bridle 1982 and references therein). For example, the brighter jet in NGC 315 expands with $dR/dz \simeq 0.1$ within 3.5 kpc of the nucleus, flares with $dR/dz \simeq 0.3$ at $z \simeq 5$ kpc, re-collimates ($dR/dz = 0$) at $z \simeq 45$ kpc and re-expands with $dR/dz = 0.1$ for $z \gtrsim 100$ kpc. Other sources show qualitatively the same behaviour, but with different scale heights, and often without the re-expansion stage. The low-luminosity jets cannot be expanding freely over the whole of their lengths, as this would require their opening angles to be constant. Re-collimation in two-sided jets occurs at similar distances on either side of the nucleus, so some global property determines the scale; the pressures needed to confine these regions are consistant with those inferred from the X-ray emission of hot gas around radio galaxies. In contrast, this pattern is not seen in the M87 jet (which expands rather suddenly at the brightest knot). None of the quasar jets are sufficiently resolved to determine their collimation properties. It is unlikely that these jets can be confined by thermal pressure.

Surface-brightness rarely decreases with radius as rapidly as would be expected for a steady, constant-velocity, flux-conserving flow with no particle acceleration or other disturbance, for which $T_B \propto R^{-2.6}$ in the B_t-dominated region. The observed relations typically are in the range $T_B \propto R^{-0.7}$ to $R^{-1.4}$. Taken with the very short synchrotron lifetimes for electrons radiating at optical and X-ray wavelengths, this provides strong evidence for some combination of deceleration (e.g. by entrainment), field amplification and acceleration of relativistic particles within radio jets.

The physical parameters of the jet material are in general poorly determined: a secure lower limit to the pressure is given by the minimum

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value for relativistic particles and magnetic fields alone, but the magnetic field is assumed to have its equipartition value, an assumption which may be substantially in error. It has generally been assumed that densities of thermal electrons can be derived from observations of Faraday rotation and depolarization. There are three serious problems with this procedure. Firstly, there is evidence for magnetic fields ordered on kpc scales and associated with gas in radio galaxies, but in front of rather than within the radio-emitting regions. (Perley, Bridle & Willis, in preparation; Laing & Bridle, in preparation). This produces variations of rotation measure across the sources. Secondly, cool, dense gas appears to surround atleast some radio lobes and, as van Breugel (1982) points out, produces depolarization at radio wavelengths. In the past, it has been assumed that these effects are due to thermal matter within the radio sources, whose density has therefore been overestimated. Thirdly, the internal density required to produce a given depolarization depends on the spectrum of scale sizes of the magnetic field, which is unknown, as well as on the density. I conclude that there are no reliable measurements of internal densities for jets. In turn, this means that *most of the methods for estimating jet velocities which require knowledge* of the density, are very much less accurate than has previously been thought.

I conclude that the occurrence and systematics of large-scale radio jets are now becoming clear, but that the estimation of their physical parameters is still extremely difficult.

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