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SYSTEMATICS OF LARGE-SCALE RADIO JETS

Alan H. Bridle
National Radio Astronomy Observatory VLA Program
and
Department of Physics and Astronomy, University of New Mexico

ABSTRACT Radio jets occur in sources with a wide range of radio luminosities, and in 70% to 80% of nearby radio galaxies. There may be two basic types of large-scale (>1 kpc) jet -- *$B_{\parallel}$-dominated one-sided jets* in sources with luminous radio cores, and *$B_{\perp}$-dominated two-sided jets* in sources with weak radio cores. The large-scale jets that have been observed at high linear resolution are well collimated within a few kpc of their cores, then flare and recollimate further out. Their brightness-radius evolution is often "subadiabatic".

1. TERMINOLOGY

The extended radio lobes of many extragalactic sources are linked to small-diameter cores at the centers of the optical objects by narrow bridges of radio emission (e.g. Fig. 1). Such bridges are usually called *jets*, although there is no direct evidence for matter transport along them. The term *jet* is popular because the bridges occur where it has been *postulated* that collimated outflows of relativistic fluid transport energy from the cores to the lobes, as continuous *beams* (Blandford and Rees 1974) or as trains of discrete *plasmoids* (Christiansen *et al.* 1977).

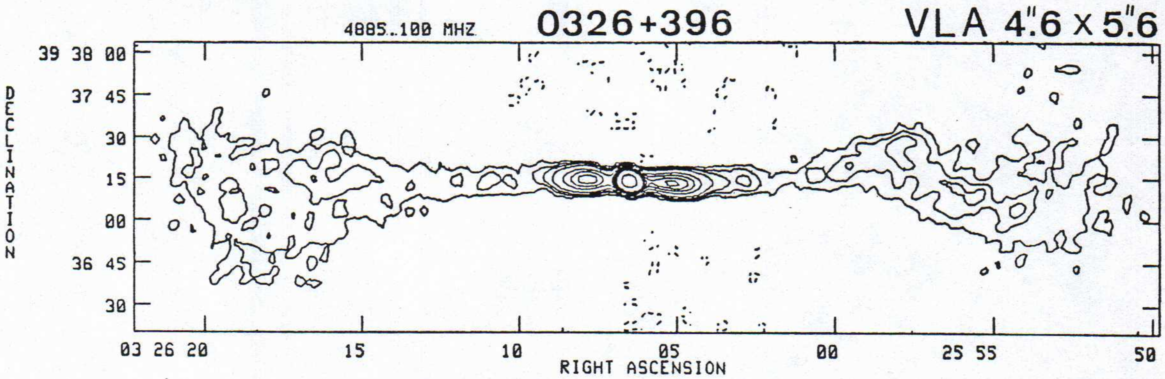

Figure 1. Jet in the radio galaxy 0326+396 at 6cm.

Use of the word *jet* prejudges the physics of the bridges. It presumes that they arise directly from radiative inefficiencies in the postulated fluid flows. In fact, the *direct* evidence for outflow from the cores of extragalactic sources (e.g., proper motions of VLBI components, asymmetries in optical emission line profiles) does not relate explicitly to material in the *large-scale* bridges. As the observers' terminology can bias thinking about the phenomena, it is dangerous to employ language which prejudges the physics without placing clear restrictions on its use. I call a feature a *jet* only if (a) its length is at least four times its width, (b) high-resolution maps separate it from other source components either spatially or by brightness contrast, and (c) it points from a radio core towards a lobe or a "hot spot".

2. OCCURRENCE OF RADIO JETS

Radio jets are now known in 69 extragalactic sources; this number is growing rapidly as high-resolution maps with good sensitivity and dynamic range are made of large samples of extended sources. Jets are found in sources with a wide range of radio luminosities, from weak ($P_{1400} \sim 2 \times 10^{23}$ W/Hz, $H_0 = 100$) radio galaxies such as M84 and NGC 3801 to powerful ($P_{1400} \gtrsim 10^{27}$ W/Hz) radio quasars such as 3C334 and 4C29.68 (Wardle *et al.*, this volume) and 3C345. Jets occur in sources with both "edge-darkened" and "edge-brightened" overall morphologies.

Jets are detected most frequently in lower-luminosity sources. At least 15 of the 22 3CR galaxies at $z < 0.05$, $\delta > 10^{\circ}$ with $P_{178} > 10^{23}$ W/Hz (this luminosity cutoff excludes only M82) have detectable radio jets. Ekers *et al.* (1981) detect jets in 9 of 11 *well-resolved* sources in a complete sample of 40 B2 galaxies with $m_{pg} < 15.7$, $S_{408} > 0.2$ Jy and $24^{\circ} < \delta < 40^{\circ}$. This 70% to 80% incidence of detectable jets in weaker radio galaxies may not apply to more powerful sources; only $\sim$25% of the 3CR "complete sample" sources so far observed at the VLA have detectable jets. Jets may therefore emit a greater fraction of the total luminosity in intrinsically weaker extragalactic sources.

Radio jets exist on size scales ranging from parsecs to hundreds of kpc, e.g., the 250-kpc jet and 400-kpc counterjet in NGC315 (Willis *et al.* 1981) and the one-sided 0.7-pc jetlike feature extending from the core of the source towards the brighter large-scale jet (Linfield 1981). This review outlines some systematic properties of jets on scales >1 kpc, based on maps of the 69 presently known jets. These data are *not* from an unbiased sample, so trends reported here must be re-examined when homogeneously-observed "complete samples" of sources with radio jets become available.

3. MAGNETIC CONFIGURATIONS

Linear polarizations in radio jets are typically 10% to 40% at centimetre wavelengths (values as high as 60% were found at 20cm in the

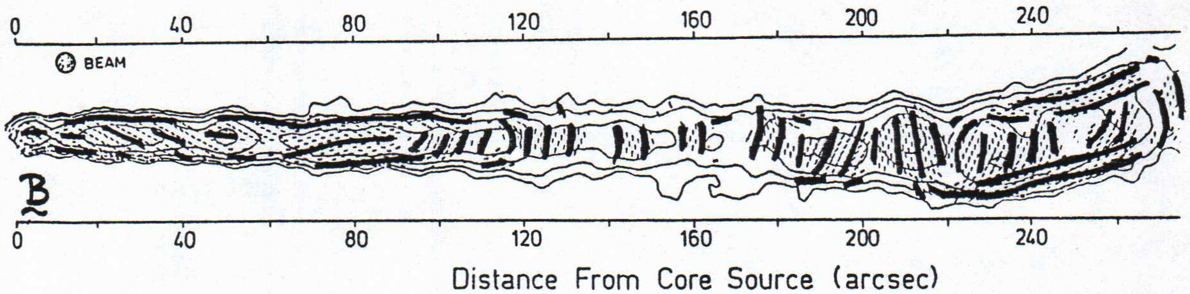

Figure 2. Projected magnetic field in the NGC6251 jet.

jets of NGC315 by Willis *et al.* 1981). Multi-frequency polarimetry can determine the rotation measures and hence the projected magnetic field configurations. Figure 2 illustrates the field configurations commonly found in jets. Close to the radio core the field is predominantly *parallel* to the jet. Further out the field on the jet axis is predominantly *perpendicular* to the jet while that on the edges may be *either* parallel or perpendicular. I will label field configurations $B_{\parallel}$ or $B_{\perp}$ according to which component prevails *on the jet axis.*

Figure 3 shows that the fraction of the jet length over which $B_{\parallel}$ dominates is strongly related to the radio core luminosity. This relation is strong enough to suggest that there are two basic types of jet distinguishable by their magnetic properties -- *$B_{\perp}$-dominated jets* associated with weak ($P_{5000} \lesssim 10^{23}$ W/Hz) cores and *$B_{\parallel}$-dominated jets* associated with more powerful cores. Note that although $L_{\parallel}/L_{jet}$ is independent of projection (in straight jets) and of redshift, there could be a selection effect present in Fig. 3. The higher-luminosity cores are in more distant sources, so the transverse resolution of the

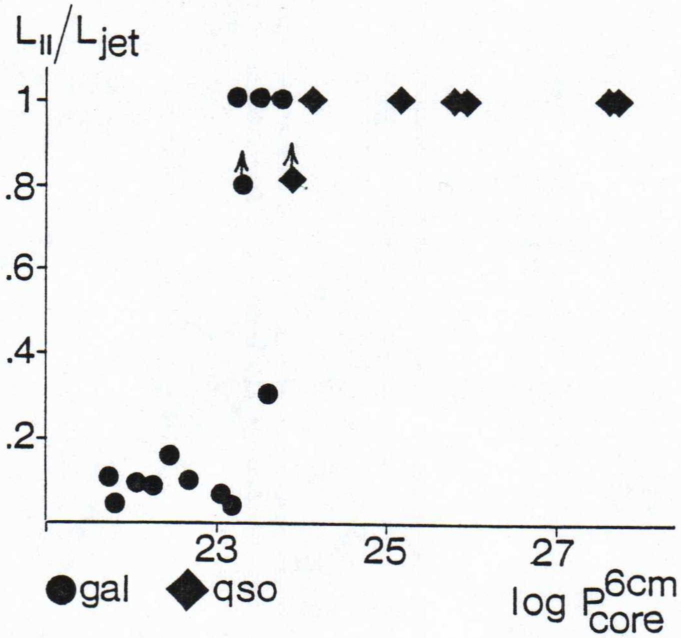

Figure 3.
The fraction of the jet length over which $B_{\parallel}$ dominates, plotted against the logarithm of the 6cm core luminosity in W/Hz for 20 jets with known magnetic configurations.

field configuration decreases from left to right. This might bias the result if, for example, more luminous sources had stronger $B_{\parallel}$ *edges* to outer $B_{\perp}$ regimes. It will be important to test the relation in Fig. 3 in samples with similar linear resolution for sources of all powers.

The short $B_{\parallel}$ regions of $B_{\perp}$-dominated jets are those closest to the cores, as expected in flux-conserving expansions where $B_{\parallel} \propto 1/R^2$ and $B_{\perp} \propto 1/R$, R being the jet radius. The presence of $B_{\parallel}$ edges to some $B_{\perp}$ regions may indicate either that $B_{\parallel}$ is maintained by shearing at the edges of some jets, or that the field has an overall helical structure. Field strengths estimated by equipartition calculations range from $\sim 2 \times 10^{-4}$ gauss in some quasar jets to $\sim 10^{-6}$ gauss in galaxy jets.

4. JET-COUNTERJET ASYMMETRIES

Figure 4 is a logarithmic histogram of the intensity ratios between jets and their counterjets at corresponding distances on opposite sides of the parent objects. The symbols code the magnetic configurations in the jets where the intensities were measured. The ratios were taken from maps on which the jet widths were poorly resolved, to integrate over their transverse intensity profiles. The ratios plotted with triangles are *lower limits*, i.e., the jets were detected only on one side of the parent object. Most $B_{\perp}$ regions have side-to-side intensity ratios <4:1 while most $B_{\parallel}$ regions have ratios >4:1 (the exceptions are a symmetric $B_{\parallel}$ regime near the core of 3C449 (Cornwell *et al.*, this volume) and the $B_{\perp}$ outer jet of NGC6251). The division of Fig. 3 into $B_{\parallel}$-dominated and $B_{\perp}$-dominated jets therefore parallels a division into *one-sided (>4:1)* and *two-sided (<4:1)* jets.

The short $B_{\parallel}$ regimes at the bases of $B_{\perp}$-dominated jets have side-to-side intensity ratios as high as those of $B_{\parallel}$-dominated jets. They usually occur at the base of the *brighter* jet in a two-sided system. Their high side-to-side ratios result in a longer "gap" between the core and the start of the jet on the *fainter* side of such systems.

In 7 of 10 sources with *both* a "VLBI" jet in the radio core *and* a large-scale jet system, the brighter large-scale jet is on the same side of the core as the VLBI jet. The asymmetries of the parsec and kpc scales in such sources may therefore be partly correlated.

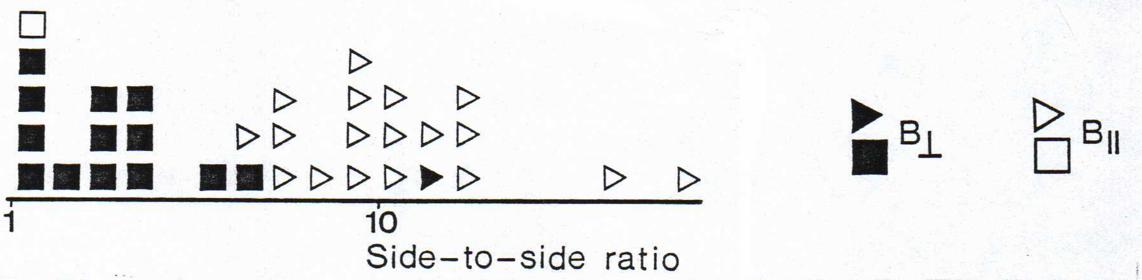

Figure 4. Jet-counterjet intensity ratios (bin width = × 1.259).

5. COLLIMATION

Eight of the nearer jets in radio galaxies (NGC315, 3C31, 0326+396, NGC6251, M84, 1321+319, Cen A and 3C449) have been mapped with adequate transverse resolution to show their lateral expansion directly. These jets are all $B_\perp$-dominated. The data for NGC315 exemplify the systematic properties that are becoming clear. Figure 5 plots the HWHM (R) of the brighter jet in NGC315 against the angular separation (z) from the core from 60" to 800" (15 to 190 kpc). The local *expansion rate* dR/dz varies from >0.23 near the core to -0.04 on the collimation "plateau" 45 to 100 kpc from the core. Beyond 100 kpc the jet re-expands with dR/dz $\sim$ 0.09. Similar variations of dR/dz occur in 3C31 (Bridle *et al.* 1980), 0326+396, NGC6251 (Willis *et al.* 1982), 1321+319 (Fanti and Parma 1981) and 3C449 (Perley *et al.* 1979). The *constant* expansion rate expected in simple freely-expanding supersonic jets is rare, and early attempts to estimate Mach numbers M for jets by putting M = dz/dR now appear to have been premature.

Recent VLA observations of the first few kpc of the jets in NGC315, NGC6251 (Willis *et al.* 1982), Cen A (Feigelson *et al.*, this volume) and M84 (Laing and Bridle 1982) show a consistent pattern of collimation behavior closer to their cores. Figure 6 *(next page)* illustrates the pattern with data on NGC315. For the first 15" (3.5 kpc) the expansion is slow (dR/dz $\lesssim$ 0.09) but the jet "flares" to dR/dz $\sim$ 0.3 by 20" (5 kpc) from the core. The collimation properties of these large-scale jets are evidently *not* set once and for all at the sub-kpc scales characteristic of VLBI jets. Rather, the observed expansions imply that the jets "break out" from confinement on scales $\lesssim$1 kpc, "flare", and then *recollimate* on scales of tens of kpc.

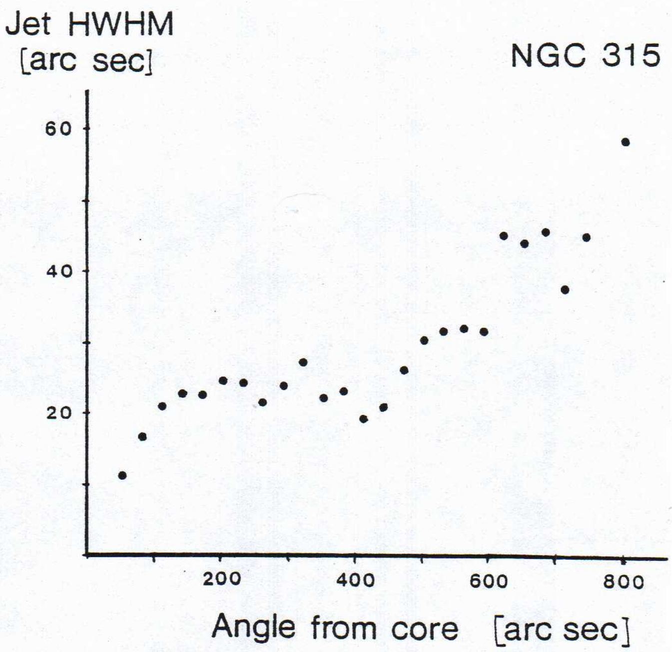

Figure 5.
The lateral expansion of the brighter jet in NGC315. 20cm WSRT data from Willis *et al.* (1981).

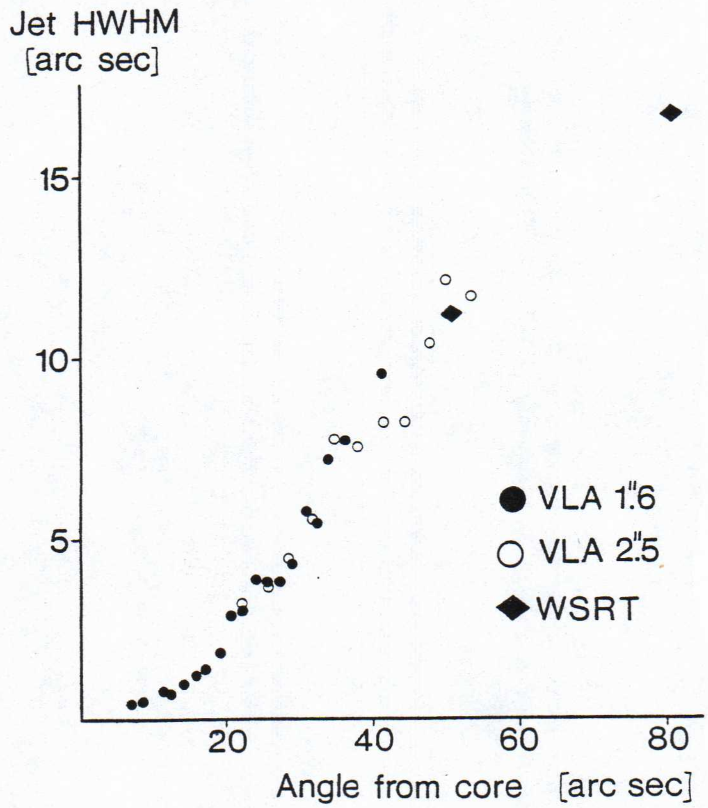

Figure 6.
The lateral expansion of the brighter jet in NGC315 (unpublished VLA 20cm data and inner WSRT data from Fig. 5). Note the excellent agreement between HWHMs measured at different resolutions.

In these nearby radio galaxies, the recollimation could be due to thermal pressures in extensive components of the galactic atmospheres (e.g., Bridle *et al.* 1981). The pressures needed to recollimate these jets could be provided by media whose X-ray emission is near the detection limits of the recent *Einstein* observations, if the pressures in the jets are near those of the radiating particles in equipartition. In this case the recollimation of *two-sided* jets should occur at similar distances from the core on both sides of the galaxy. This appears to be the case in NGC315, 3C31, 0326+396, 1321+319 and 3C449.

I have used the HWHM of the transverse intensity profiles of these jets to describe their expansion properties because most of the profiles are center-brightened and reasonably Gaussian (although flat-topped or asymmetric profiles *do* occur occasionally). No clear relation has yet emerged between the transverse profile shapes and other properties of the jets (such as the magnetic configurations or intensity gradients).

6. SPECTRA

The radio spectra of 15 jets have now been measured near 20cm. Most jets have very similar spectra; the mean spectral index is 0.6, with a standard deviation of 0.15. This is a spectral index frequently seen in SS433 (Hjellming and Johnston, this volume). Jets usually have slightly flatter spectra than the lobes they enter (Willis 1981).

There are usually only weak (<0.2) spectral index gradients along the jets and no *systematic* gradients across them. There is no discernible correlation between spectral index and expansion rate, contrary to the predictions of Benford *et al.* (1980).

7. BRIGHTNESS-RADIUS EVOLUTION

The surface brightnesses of jets rarely decrease as rapidly with increasing jet width as would be expected if they were steady, constant-velocity flux-conserving flows of unreaccelerated particles. Even if the *radiating* particles did no work in the lateral expansion of the jets, magnetic flux conservation would make the central surface brightness T_b decrease with HWHM R *at least* as fast as $1/R^{(\gamma+3)/2}$ in a jet satisfying these assumptions. (This is the dependence for a pure transverse magnetic field varying as 1/R). For the mean jet spectral index of 0.6, the *slowest* "adiabatic" brightness decline would thus be $1/R^{2.6}$.

Figure 7 exemplifies the brightness-radius evolution seen in most nearby jets, using data for NGC6251. Close to the radio core T_b initially *increases* with R, then declines slowly ($1/R^{0.7}$ here). Such regions within a few kpc of the cores are where optical continuum emission was detected in the jets of 3C31 and 3C66B (Butcher *et al.* 1980). The optical-to-radio spectral indices are similar to the radio indices in these regions, requiring *in situ* particle replenishment unless the magnetic fields are far below their equipartition values.

In the "flaring" regions further from the cores the *mean* T_b-R relations in seven of nine well-studied nearby jets are significantly flatter than $1/R^{2.6}$, all seven being in the range 1/R to $1/R^{1.4}$. Only in 0326+396 and on the "collimation plateau" of NGC315 does the brightness fall off as steeply as, or steeper than, $1/R^{2.6}$ for a significant fraction of the length of the jet.

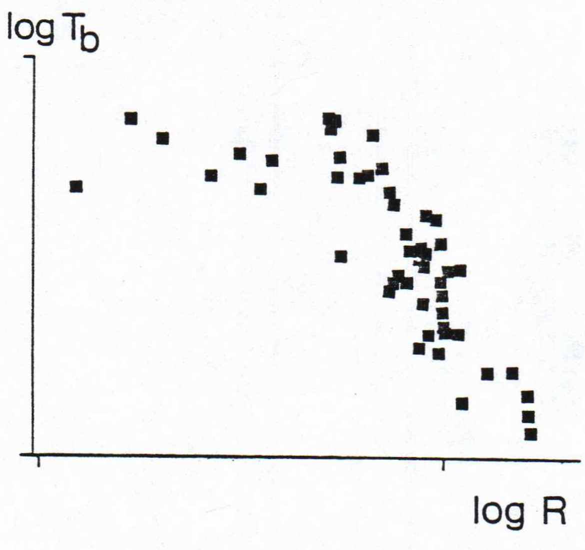

Figure 7.
Logarithmic plot of brightness temperature T_b on the axis of the jet in NGC6251 against the jet HWHM, over the first 3' (60 kpc) of the jet. The HWHM does not increase monotonically, due to knots in the jet, but the *mean* T_b-R relation is well-defined and evolves from $1/R^{0.7}$ to $1/R^{1.4}$ as the jet expands.
(VLA 1662-MHz data on arbitrary scales of T_b and R)

Such "subadiabatic" brightness-radius relations could arise in several ways, including (a) deceleration of the jet by entrainment of low-momentum material so that the jet is compressed longitudinally to compensate for its lateral expansion, (b) magnetic flux amplification, (c) relativistic particle acceleration or replenishment, or (d) decline of the power output of the core over the lifetime of the jet. In several jets the regimes of *faster* expansion are those of *slower* brightness-radius evolution. This may be consistent with interpreting them as turbulent mixing regions in which the emission of MHD waves and their damping by acceleration of relativistic particles is an effective source of viscosity on small scales (Henriksen *et al*. 1982).

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REFERENCES

Benford,G., Ferrari,A. and Trussoni,E. 1980. Ap.J., 241, pp. 98-110.

Blandford,R.D. and Rees,M.J. 1974. M.N.R.A.S., 169, pp. 395-415.

Bridle,A.H., Chan,K.L. and Henriksen,R.N. 1981. J.Roy.Astron.Soc. Canada, 75, pp. 69-93.

Bridle,A.H., Henriksen,R.N., Chan,K.L., Fomalont,E.B., Willis,A.G. and Perley,R.A. 1980. Ap.J.(Letters), 241, pp. L145-L149.

Butcher,H.R., van Breugel,W.J.M. and Miley,G.K. 1980. Ap.J., 235, pp. 749-754.

Christiansen,W.A., Pacholczyk,A.G. and Scott,J.S. 1977. Nature, 266, pp. 593-596.

Ekers,R.D., Fanti,R., Lari,C. and Parma,P. 1981. Preprint.

Fanti,R. and Parma,P. 1981. *Optical Jets in Galaxies* (Proc. 2nd ESO/ESA Workshop, 18-19 February 1981), pp. 91-95.

Henriksen,R.N., Bridle,A.H. and Chan,K.L. 1982. Ap.J., submitted.

Laing,R.A. and Bridle,A.H. 1982. In preparation.

Linfield,R.P. 1981. Ap.J., 244, pp. 436-446.

Perley,R.A., Willis,A.G. and Scott,J.S. 1979. Nature, 281, pp. 437-442.

Willis,A.G. 1981. *Optical Jets in Galaxies* (Proc. 2nd ESO/ESA Workshop, 18-19 February 1981), pp. 71-76.

Willis,A.G., Perley,R.A. and Bridle,A.H. 1982. In preparation.

Willis,A.G., Strom,R.G., Bridle,A.H. and Fomalont,E.B. 1981. Astron. Astrophys., 95, pp. 250-265.