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3C380: a powerful radio source seen end-on?

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SUMMARY

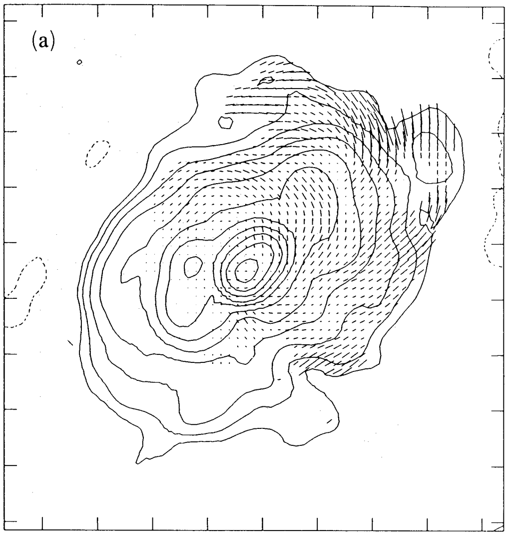
We present new VLA, MERLIN and VLBI observations of 3C380, a powerful compact steep-spectrum radio source with complex extended structure, and attempt to clarify whether it is a larger source seen end-on or whether it is intrinsically of galactic dimensions and distorted. The extended structure, which could be a pair of overlapping lobes, exhibits a strong depolarization asymmetry of the kind found in powerful double sources, while the core exhibits superluminal motion with $v_{\rm app} \sim 8\ c$. 3C380 therefore has features to be expected of a Fanaroff–Riley class II source seen approximately end-on. However, from a detailed consideration of the new evidence we infer that the source is intrinsically small with an overall extent $\leqslant 60$ kpc. This small size, together with several unusual features of the structure, suggests that it may be interacting strongly with the surrounding gas.

1 INTRODUCTION

The quasar 3C380 ($z = 0.692$) has a steep radio spectrum and is one of the most intrinsically powerful cosmic radio sources, with a luminosity of $\sim 10^{28}$ W Hz^{-1} sr^{-1} at 178 MHz. The majority of powerful steep-spectrum sources have FRII structures (Fanaroff & Riley 1974), i.e. two dominant edge-brightened lobes straddling a relatively weak core. However, 3C380 does not fit into this pattern. Instead it has a relatively strong core, which dominates the spectrum above ~ 20 GHz, surrounded by a tangle of emission whose underlying structure is far from clear (Wilkinson *et al.* 1984). 3C380 is often classified as a compact steep-spectrum source (CSS) despite its extended structure, since most of its radio emission at 5 GHz apparently comes from a region of galactic dimensions rather than hundreds of kpc which is typical of FRII sources. It certainly does not look like a typical FRII quasar, but the effects of projection and relativistic aberration can markedly affect the observed structures of sources inclined at small angles to the line-of-sight (Gower *et al.* 1982). The peculiarities of 3C380 as a radio source may be more apparent than real. This paper presents new radio maps of 3C380 made with the VLA, MERLIN, and a global VLBI array and attempts to answer the following query – is the peculiar radio appearance of 3C380 merely a result of viewing a typical FRII source at a special angle or is it an intrinsically rather small and distorted radio source?

2 OBSERVATIONAL RESULTS

Fig. 1(a) and (b) shows VLA maps at 1.6 and 5 GHz with an angular resolution of 1 arcsec in which the fractional polarization vectors are superposed on the total intensity contours. Vectors are plotted at $\geqslant 3$ times $\sigma_{\rm pol} = \sqrt{\sigma_{Q^2} + \sigma_{U^2}}$, where σ_Q and σ_U are the rms noise on the blank sky in the distribution of the Stokes parameters Q and U. The surface-brightness sensitivity of the 1.6-GHz map is superior to that of the 5-GHz map but both maps reveal a 'halo', not seen in the MERLIN maps (Wilkinson *et al.* 1984; Flatters 1987) at 1.6 GHz, whose dimensions are $\sim 14 \times \sim 10$ arcsec (i.e. ~ 56 $h^{-1} \times \sim 40$ h^{-1} kpc for $H_0 = 100$ h km s^{-1} Mpc^{-1}). The distribution of polarized emission is strikingly different in these two VLA maps. At 5 GHz the typical degree of polarization over most of the source is ~ 15 per cent. But at 1.6 GHz, while the region on the NW side is polarized to about the same degree as at 5 GHz, the south-east (SE) side is $\leqslant 1$ per cent polarized. The depolarization across the face of the source is therefore highly asymmetrical. Fig. 2(a) is a VLA map at 5 GHz (resolution 0.35 arcsec) with the polarized intensity vectors superposed on the total intensity contours. These contours confirm the MERLIN maps (Wilkinson *et al.* 1984; Flatters 1987) at 1.6 GHz and show the bright central core and the two knots (barely resolved in this map) ~ 1 arcsec, i.e. ~ 4 h^{-1} kpc, to the north-west (NW); the 'arc of emission' (Wilkinson *et al.* 1984) is also clearly revealed. Fig. 2(b), which is a VLA map at 15 GHz (resolution 0.1 arcsec) again with the polarized intensity vectors superposed, shows that the knot nearer the core (knot A) is compact but the one further to the NW, the 'NW complex', is extended and has a more complicated structure. The central core has a rotation measure (RM) $= +130 \pm 5$ rad m^{-2} and elsewhere across the face of the source the RM is typically some tens of rad m^{-2}; the position angles of the electric vectors in Figs 1 and 2 are therefore close to the intrinsic angles at both 5 and 15 GHz.



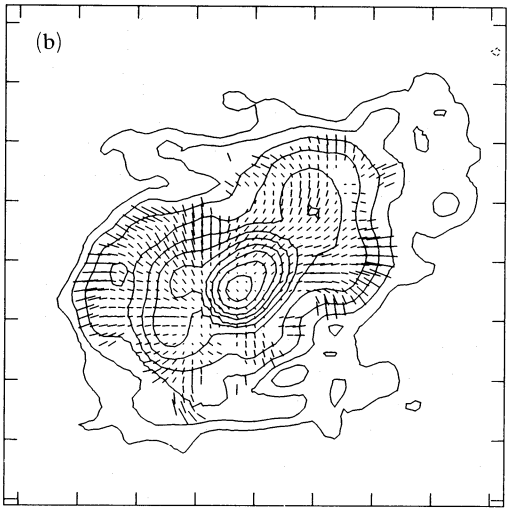
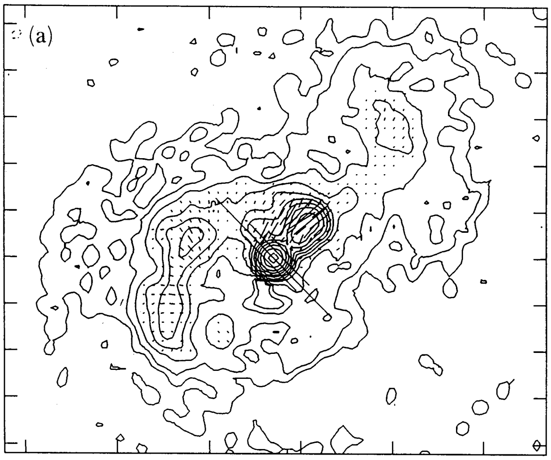


Figure 1. (a) VLA map at 1.6 GHz (resolution 1 arcsec) with fractional polarization ***E***-vectors superposed; contour levels are $3\times(-1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 512$ and $1024)$ mJy per beam and the peak brightness is 4.32 Jy per beam. A vector of length 1 arcsec represents a fractional polarization ratio of 0.67. The tick marks represent 2 arcsec. (b) VLA map at 5 GHz (resolution 1 arcsec) with fractional polarization ***E***-vectors superposed; contour levels are $1.8\times(-1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 512$ and $1024)$ mJy per beam and the peak brightness is 2.84 Jy per beam. A vector of length 1 arcsec represents a fractional polarization ratio of 0.67. The tick marks represent 2 arcsec.



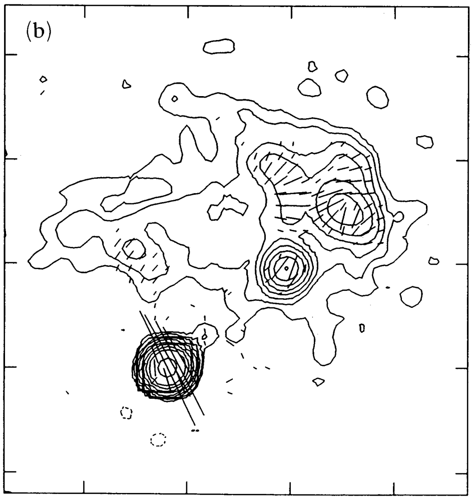


Figure 2. (a) VLA map at 5 GHz (resolution 0.35 arcsec) with polarized intensity ***E***-vectors superposed; contour levels are -1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024 and 2048 mJy per beam and the peak brightness is 2.63 Jy per beam. A vector of length 1 arcsec represents a polarized intensity of 50 mJy per beam. The tick marks represent 1 arcsec. (b) VLA map at 15 GHz (resolution 0.1 arcsec) with polarized intensity ***E***-vectors superposed; contour levels are -1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 512 and 1024 mJy per beam. The peak brightness is 1.79 Jy per beam. A vector of length 1 arcsec represents a polarized intensity of 44 mJy per beam. The tick marks represent 0.5 arcsec.

3 DISCUSSION

Wilkinson *et al.* (1984) puzzled over the complicated structure of 3C380 and rejected the idea that 3C380 is a typical FRII source seen approximately end-on, principally on the grounds that the *a priori* probability of the axis lying close enough ($\leqslant 15°$) to the line-of-sight, so that the lobes overlap to give an apparently continuous 'halo', is $\leqslant 1$ per cent. Subjectively they also judged that 3C380 did not look like a relatively simple FRII source seen in projection. However, as well as our new information on 3C380, much more is now known about the phenomenology of FRII sources. We have therefore re-examined the possibility that this particular CSS is a much larger source seen almost end-on. In fact, several features of 3C380 are consistent with this interpretation.

The halo: there are a significant minority of the FRII quasars (typically an order of magnitude less luminous than 3C380) which have lobes of about the same dimensions as the 3C380 halo (e.g. Leahy, Muxlow & Stephens 1989; Bridle *et al.*, unpublished). Both the spectral index, $\alpha = 1.0 \pm 0.2$, of the halo (defined as $S_\nu \propto \nu^{-\alpha}$), and its RM (10 s of rad m^{-2}) are typical of FRII lobes (Leahy *et al.* 1989; Perley 1989).

The NW knots and the arc: knot A is more compact (~ 0.040 arcsec, i.e. $\sim 160\ h^{-1}$ pc, Wilkinson *et al.* 1984) than is apparent from Fig. 2(b), while the NW complex has a characteristic linear dimension of $\sim 1\ h^{-1}$ kpc. These knots are brighter than the typical hotspots in FRII sources but together they bear a striking resemblance to the primary and secondary components of 'double hotspots' seen in the lobes of some FRII sources (Laing 1989) – for example the southern lobes of 3C205 and 3C268.4 (Lonsdale & Barthel 1986). The arc also strongly resembles bright curved features observed in the lobes of some FRII sources, especially those in the SE lobes of Cygnus A (Dreher, Carilli & Perley 1987) and 3C295 (Baum *et al.* 1988; Akujor, Spencer & Wilkinson 1990). The apparent length of the 3C380 arc is ~20 h^{-1} kpc, while these FRII 'lobe arcs' have linear sizes typically 5–20 kpc. The NW complex and the arc have polarizations of 10–15 per cent at 5 GHz, similar to those seen in FRII hotspots (e.g. Dreher 1981; Rudnick & Anderson 1990; P. Leahy, private communication). The magnetic field direction follows the ridge line of the arc (Fig. 2a) as it does in the arc in the SE lobe of Cygnus A (Dreher *et al.* 1987) which almost certainly marks the path of backflowing material from the hot spots.

The energy flow: we can establish the path of at least part of the energy flow by analogy with the widely accepted model (Begelman, Blandford & Rees 1984) of energy transport in radio sources. Energy passes down a narrow beam or jet from an active nucleus, is decelerated in the hotspots and then flows back into the extended lobes. The initial path of a jet in 3C380 can be seen in Fig. 3 which is a MERLIN map at 5 GHz (resolution 0.080 arcsec) of the core and knots with, inset, a VLBI map at 5 GHz (resolution 0.0015 arcsec) of the core (Wilkinson *et al.* 1990). The VLBI map shows a bright nucleus near the SE tip and a one-sided jet, visible out to ~0.035 arcsec, i.e. ~140 h^{-1} pc, towards the NW; this jet can then be traced in the MERLIN map to knot A. Other observations show that knot A is edge-brightened on the side facing the core (Wilkinson *et al.* 1984; Simon *et al.* 1990) which suggests that it is indeed interacting with the beam. In the core the magnetic field is approximately parallel to the jet, while in knot A it is approximately perpendicular to the jet, consistent with field compression at a shock. This observed field orientation is similar to those seen in FRII sources. The magnetic field is parallel to the ridge lines in the NW complex and the arc. These observations suggest a flow from the nucleus to knot A, where at least part of the flow is diverted into the NW complex (Lonsdale & Barthel 1986; Lonsdale 1989) and the arc and finally, presumably, into the halo. The spectral indices of knot A, the arc and the halo, 0.6, 0.75 and 1.0, respectively, support this interpretation. In broad terms, therefore, our results on 3C380 are consistent with current ideas regarding energy transport in FRII sources.

The depolarization anisotropy: the greater depolarization of the emission from the counter-jet side in 3C380 is the norm in FRII quasars (Laing 1988; Garrington *et al.* 1988). While the interpretation of this phenomenon remains a matter of some debate, a likely explanation is that the whole source is embedded in a large-scale magneto-ionic medium with the jet side of the source pointed at us and the counter-jet side pointed away from us. This model has two observational consequences: first, if the material in the forward-pointing jet is moving relativistically, its emission will be 'Doppler-boosted' compared with that from the counter-jet and hence will be much easier to see. Secondly, the fact that the radiation from the counter-jet side has to traverse a greater Faraday depth will tend to cause a larger 'beam depolarization' if the magneto-ionic medium contains substructure on scales smaller than the beam (Burn 1966). Thus the fact that 3C380 is preferentially depolarized on the counter-jet side is direct evidence to link it with extended FRII sources. It is also model-dependent evidence that the NW part of the source is the near side while the SE part is the far side.

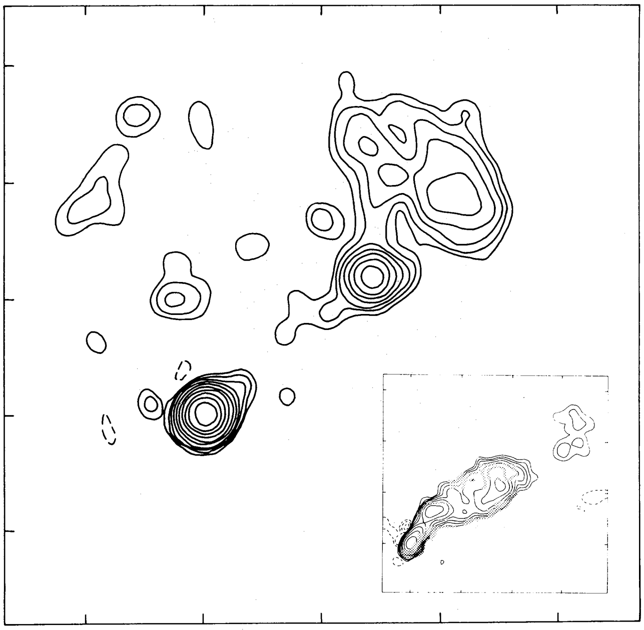


Figure 3. MERLIN map at 5 GHz (resolution 0.080 arcsec); contour levels are 2.49 × (−1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 512) mJy per beam, and the peak brightness is 2.49 Jy per beam. The tick marks represent 0.4 arcsec. Inset: VLBI map at 5 GHz (resolution 0.0015 arcsec); contours 0.619 × (−8, −4, −2, 2, 4, 8, 16, 32, 64, 128, 256 and 512) mJy per beam. The tick marks represent 0.008 arcsec.

Superluminal motion: comparison of VLBI images made at a number of epochs has shown that the outer regions of the jet (see inset in Fig. 3) are moving away from the core at 0.36 ± 0.09 mas yr^{-1} corresponding to an apparent velocity $v_{\mathrm{app}} = (8 \pm 2)\ h^{-1}\ c$ (Wilkinson *et al.* 1990, and in preparation). For the limiting case $v_{\mathrm{jet}} = c$, the inferred angle θ, at which the outer part of the VLBI-scale jet is inclined to the line-of-sight, is ~10° (Blandford & Königl 1979). θ cannot be much less than this, or such a large v_{app} could not be observed.

While these properties of 3C380 are those expected from an FRII source seen end-on, other features make us think that simple projection effects cannot be the only reason why 3C380 looks so peculiar.

The core strength: such a small angle of inclination for the *overall* axis of the source appears to be inconsistent with the strength of the core relative to the extended structure. The 'unified scheme' (Blandford & Königl 1979; Orr & Browne 1982; Kapahi & Saikia 1982) for radio-loud quasars attributes the major differences between the 'core-dominated' sources and the 'lobe-dominated' sources to the effects of projection, and the relativistic amplification of the core emission when the source is viewed close to the line-of-sight.

A projection angle, θ, of ~10° is similar to that expected for a flat-spectrum core-dominated source, whereas 3C380 is dominated by extended steep-spectrum emission at frequencies below 20 GHz. We can quantify this dichotomy using Orr & Browne's model of a typical quasar and assuming a value for the Lorentz factor γ of the core. If $\gamma \geqslant 5$ the radio core of 3C380 is underluminous by a factor of $\geqslant 10$. A possible way out of this dilemma is to suggest that there is an intrinsic bend in the jet close to the core such that, while the overall source axis is within 10° of the line-of-sight, the jet in the core points ~30° away. This is consistent with the fact that no strong variability has been observed at centimetre (e.g. Seielstad, Pearson & Readhead 1983) and optical (Grandi & Tifft 1974) wavelengths. In addition, the optical polarization of ~1 per cent (Wills 1989) and the measured FWHM of the Hβ line, 4900 km s^{-1} (N. Jackson, private communication), are typical of lobe-dominated quasars (Wills & Browne 1986; Jackson *et al.* 1989) and hence suggest a larger projection angle for the initial part of the jet. The inferred bend angle of ~20° between the innermost jet and the outer hotspots is unusual for FRII sources in which the inner and outer jets are typically aligned to better than 10° (Browne 1987). Projection effects will reduce the apparent size of the source but even if $\theta \approx 10°$ the bright knots in the north-western complex of 3C380 still lie within ~25 h^{-1} kpc of the nucleus. Thus, if 3C380 is an FRII source, it must be a small one.

The depolarization of the arc: Fig. 1(a) and the 1.6-GHz MERLIN map (Flatters 1987) show that the arc is depolarized at 1.6 GHz over most of its length. If the depolarization *is* due to a large-scale magneto-ionic medium then the jet is on the near-side of the source, as is the initial, polarized, part of the arc. On this basis the rest of the arc lies behind the core. If $\theta \approx 10°$ then the arc would have to be $\geqslant 80$ kpc long to produce the observed effect – such a feature would be unique among powerful radio sources. It is, however, conceivable that the arc is physically associated with the more distant lobe, but projection effects conspire to make it appear as a continuation of the extensions in the north-western complex.

Atypical FRII features: the significant polarization of the emission beyond the NW complex (see Fig. 2a), in a region where the total intensity contours themselves hint at a weak jet in the same position angle as that of the original jet, suggests that not all of the energy of the beam is dissipated in the north-western complex and the extensions leading from the hotspots (Fig. 3). This 'weak jet' emission does not depolarize at 1.6 GHz, which is consistent with it being a continuation of the original jet on the near side of the source. The polarization of knot A, 2.8 per cent at 5 GHz, is also an order of magnitude lower than that seen in the primary hotspots in FRII sources like 3C205 and 3C268.4 (Lonsdale & Barthel 1986) and suggests that there may be more thermal gas in or around this knot than in FRII hotspots. Finally, the cut-off of the polarized emission in the SE part of the source at 1.6 GHz is much sharper than is seen across the face of FRII sources (Garrington *et al.* 1988). In FRIIs a spherical 'X-ray halo' is the favoured candidate for the depolarizing screen but in 3C380 this screen seems more likely to be disc-like. In this it may be similar to Centaurus A in which the inner southern radio lobe also shows a sharp reduction in depolarization about 6.5 kpc from the nucleus. Burns & Clarke (1990) attribute this to the effect of foreground gas in the dust lane of the galaxy. The [O III]λ5007 line in 3C380 is prominent (N. Jackson, private communication) and we speculate that future high-resolution optical observations of this quasar, particularly with the HST, may reveal extended line-emitting gas in a disc.

4 CONCLUSIONS

The CSS quasar 3C380 exhibits several features expected of an FRII source seen approximately end-on, namely (i) superluminal motion in the core; (ii) a halo, which could be the overlapping lobes; (iii) the depolarization anisotropy across the face of the source; (iv) the similarity of the NW knots to double hotspots in FRII lobes. However, not all of 3C380's features can be so easily accounted for by projection close to the line-of-sight. In particular (v) the core is relatively weak and is not strongly variable at radio or optical wavelengths; and (vi) the arc, if it is a single feature, would have to extend from the front round to the back of the source.

In respect of (i), (ii) and (v) 3C380 resembles the superluminal CSS 3C216 (Barthel, Pearson & Readhead 1989), although 3C216 has weak blazar characteristics. In both sources it is likely that projection is playing a significant role in determining the observed properties; nevertheless it seems that 3C380 is intrinsically no larger than the ~60-kpc halo seen in our maps. This small size, and the difficulty of reconciling our observations with a source having a single dominant axis, suggests that there is a stronger interaction between the energy-carrying beams and the surrounding gas than is usual in FRIIs.

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REFERENCES

Akujor, C. E., Spencer, R. E. & Wilkinson, P. N., 1990. *Mon. Not. R. astr. Soc.*, **244**, 362.
Barthel, P. D., Pearson, T. J. & Readhead, A. C. S., 1989. *Astrophys. J.*, **329**, L51.
Baum, S. A., Heckman, T., Bridle, A., van Breugel, W. & Miley, G., 1988. *Astrophys. J. Suppl.*, **68**, 643.
Begelman, M. C., Blandford, R. D. & Rees, M. J., 1984. *Rev. Mod. Phys.*, **56**, 255.
Blandford, R. D. & Königl, A., 1979. *Astrophys. J.*, **232**, 34.
Browne, I. W. A., 1987. In: *Superluminal Radio Sources*, p. 129, eds Zensus, J. A. & Pearson, T. J., Cambridge University Press, Cambridge.
Burn, B. J., 1966. *Mon. Not. R. astr. Soc.*, **133**, 67.
Burns, J. O. & Clarke, D. A., 1990. In: *Galactic and Intergalactic Magnetic Fields, IAU Symp. No. 140*, p. 469, eds Beck, R., Kronberg, P. P. & Wielebinski, R., Kluwer, Dordrecht.
Dreher, J. W., 1981. *Astr. J.*, **86**, 833.

Dreher, J. W., Carilli, C. L. & Perley, R. A., 1987. *Astrophys. J.,* **316,** 611.

Fanaroff, B. L. & Riley, J. M., 1974. *Mon. Not. R. astr. Soc.,* **167,** 31P.

Flatters, C., 1987. *Nature,* **326,** 683.

Garrington, S. T., Leahy, J. P., Conway, R. G. & Laing, R. A., 1988. *Nature,* **331,** 147.

Gower, A. C., Gregory, P. C., Hutchings, J. B. & Unruh, W. G., 1982. *Astrophys. J.,* **262,** 478.

Grandi, S. A. & Tifft, W. G., 1974, *Publs astr. Soc. Pacif.* **86,** 873.

Jackson, N., Browne, I. W. A., Murphy, D. W. & Saikia, D. J., 1989. *Nature,* **338,** 485.

Kapahi, V. K. & Saikia, D. J., 1982. *J. Astrophys. astr.,* **3,** 465.

Laing, R. A., 1988. *Nature,* **331,** 149.

Laing, R., 1989. In: *Hot Spots in Extragalactic Radio Sources, Lecture Notes in Physics No. 327*, p. 27, eds Meisenheimer, K. & Röser, H.-J., Springer-Verlag, Berlin.

Leahy, J. P., Muxlow, T. W. B. & Stephens, P. W., 1989. *Mon. Not. R. astr. Soc.,* **239,** 401.

Lonsdale, C. J., 1989. In: *Hot Spots in Extragalactic Radio Sources, Lecture Notes in Physics No. 327*, p. 45, eds Meisenheimer, K. & Röser, H.-J., Springer-Verlag, Berlin.

Lonsdale, C. J. & Barthel, P. D., 1986. *Astr. J.,* **92,** 12.

Orr, M. J. L. & Browne, I. W. A., 1982. *Mon. Not. R. astr. Soc.,* **200,** 1067.

Perley, R. A., 1989. In: *Hot Spots in Extragalactic Radio Sources, Lecture Notes in Physics No. 327*, p. 1, eds Meisenheimer, K. & Röser, H.-J., Springer-Verlag, Berlin.

Rudnick, L. & Anderson, M., 1990. *Astrophys. J.,* **355,** 427.

Seielstad, G. A., Pearson, T. J. & Readhead, A. C. S., 1983. *Publs astr. Soc. Pacif.,* **95,** 842.

Simon, R. S., Readhead, A. C. S., Moffet, A. T., Wilkinson, P. N., Booth, R., Allen, B. & Burke, B. F., 1990. *Astrophys. J.,* **354,** 140.

Wilkinson, P. N., Booth, R. S., Cornwell, T. J. & Clarke, R. R., 1984. *Nature,* **308,** 619.

Wilkinson, P. N., Tzioumis, A. K., Akujor, C. E., Benson, J. M., Walker, R. C. & Simon, R. S., 1990. In: *Parsec-scale Radio Jets*, p. 152, eds Zensus, J. A. & Pearson, T. J., Cambridge University Press, Cambridge.

Wills, B. J., 1989. In: *BL Lac Objects, Lecture Notes in Physics No. 334,* p. 109, eds Maraschi, L., Maccacaro, T. & Ulrich, M.-H., Springer-Verlag, Berlin.

Wills, B. J. & Browne, I. W. A., 1986. *Astrophys. J.,* **302,** 56.