Deep imaging of Fanaroff–Riley Class I radio galaxies with lobes

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ABSTRACT

We present deep, high-resolution imaging of the nearby Fanaroff–Riley Class I (FR I) radio galaxies NGC 193, B2 0206+35, B2 0755+37 and M84 at frequencies of 4.9 and 1.4 GHz using new and archival multifrequency observations from the Very Large Array. In addition, we describe lower resolution observations of B2 0326+39 and a re-analysis of our published images of 3C 296. All of these radio galaxies show twin jets and well-defined lobes or bridges of emission, and we examine the common properties of this class of source. We show detailed images of total intensity, brightness gradient, spectral index, degree of polarization and projected magnetic-field direction. The jet bases are very similar to those in tailed twin-jet sources and show the characteristics of decelerating, relativistic flows. Except on one side of M84, we find that the jets can be traced as least as far as the ends of the lobes, where they often form structures which we call ‘caps’ with sharp outer brightness gradients. Continuing, but less well collimated, flows back into the lobes from the caps can often be identified by their relatively flat spectral indices. The lobes in these radio galaxies are similar in morphology, spectral-index distribution and magnetic-field structure to those in more powerful (FR II) sources, but they lack hotspots or other evidence for strong shocks at the ends of the jets. M84 may be an intermediate case between lobed and tailed sources, in which one jet does not reach the end of its lobe, but disrupts to form a ‘bubble’.

Key words: magnetic fields – polarization – galaxies: jets – radio continuum: galaxies.

1 INTRODUCTION

Relativistic jets are the primary channel of energy loss from accreting supermassive black holes in many radio galaxies. They also have a major impact on their surroundings and act as accelerators of the most energetic photons (and perhaps hadrons) we observe. The present paper forms part of a study of jet physics in nearby, low-luminosity radio galaxies, specifically those with FR I morphology (Fanaroff & Riley 1974). We have developed a sophisticated model of FR I jets as relativistic, symmetrical, axisymmetric flows. By fitting to deep, high-resolution radio images in total intensity and linear polarization, we have determined the three-dimensional variations of velocity, emissivity and magnetic-field ordering in five sources (Laing & Bridle 2002a; Canvin & Laing 2004; Canvin et al. 2005; Laing et al. 2006b). We have shown that FR I jets decelerate from relativistic (\( \beta = v/c \approx 0.8 \)) to subrelativistic speeds on scales of a few kpc and that they are faster on-axis than at their edges, as expected if they entrain external material.

The physics of boundary-layer entrainment must depend on the composition and density of the surrounding medium, and in particular on whether the jets propagate in direct contact with the intergalactic medium (IGM) or are surrounded by lobes consisting primarily of tenuous and at least partially relativistic plasma. Of the five sources we have modelled, three have plumed or tailed outer structures wherein most of the extended emission appears to lie farther from the active nucleus than the narrower jets: 3C 31 (Laing & Bridle 2002a; Laing et al. 2008), B2 1553+24 (Canvin & Laing 2004; Young et al. 2005) and NGC 315 (Canvin et al. 2005; Laing et al. 2006a). We presume that their jets are in direct contact with the IGM. On the other hand, 3C 296 (Laing et al. 2006b) has two lobes with well-defined outer boundaries and a diffuse bridge of emission around the jets (at least in projection). A further source, B2 0326+39 (Canvin & Laing 2004), clearly has lobes, but it is unclear from published observations (Bridle et al. 1991) whether these lobes surround the inner jets.

Our best-fitting model for the jets in the lobed FR I source 3C 296 (Laing et al. 2006b) is unusual in that it shows a very large transverse velocity gradient across the jet except when it is very close to the nucleus, the ratio of edge to central velocity in this jet...
being $< 0.1$, compared with values $\approx 0.4$ for the jets in three tailed sources (the value for 0326$+$39 is poorly determined). It is therefore of interest to examine whether jets in other FR I sources whose lobes entirely surround them appear to decelerate differently with distance from the nucleus than those in tailed FR I sources, or those in sources whose lobes may not extend all the way back to the nucleus, leaving the inner jets unshielded. Projection complications interpretation of individual sources (the lobes may appear superimposed on the jets even if they are not in physical contact) and it is not always straightforward to separate jet and lobe emission, but the differences between 3C 296 and the rest are large. Modelling of the jets in a small number of lobed sources (which form the majority of complete samples of low-luminosity radio galaxies; Parma, de Ruiter & Fanti 1996) should therefore be enough to decide whether there are systematic differences between the two classes.

The primary aim of this paper is to present high-quality radio imaging of four lobed FR I sources whose jets are suitable for modelling by our methods. The models themselves will be presented elsewhere. Our approach to jet modelling requires fitting to high-fidelity, deep images with a linear resolution of $\lesssim 0.25$ kpc derived from multiconfiguration observations at 4.9 GHz (C band) or 8.5 GHz (X band) with the Very Large Array (VLA) at the National Radio Astronomy Observatory. In order to correct the linear polarization for the effects of Faraday rotation (small at these frequencies), we also need to observe at several frequencies in the range of 1.3–1.7 GHz (L band). High-quality images of depolarization, rotation measure and spectral index are useful by-products. In this paper, we describe

(i) details of the observations,
(ii) the source morphologies in total intensity at a range of resolutions,
(iii) images of the spectral-index distributions and
(iv) images of the degree of polarization and the apparent magnetic field direction, corrected for Faraday rotation.

We also include high-resolution MERLIN imaging for two of the sources. Faraday rotation and depolarization are analysed in detail by Guidetti et al. (2011) and Guidetti et al. (in preparation).

We also present an analysis of the spectrum of 3C 296 which improves on that given by Laing et al. (2006b) and imaging of the large-scale structure of B2 0326$+$39 to trace its lobe emission closer to the nucleus than in earlier studies. These data complete the documentation of the large-scale structures and spectral-index distributions for all of the lobed FR I sources whose jets we can currently model.

Section 2 describes the new observations and data reduction, Section 3 presents our results for the sources individually, and Section 4 outlines the phenomenology of their jets and larger scale emission as a prelude to modelling. Section 5 is a brief summary.

We adopt a concordance cosmology with Hubble constant, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_\Lambda = 0.7$ and $\Omega_M = 0.3$.

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**Table 1.** The sources. Col. 1: name (as used in this paper). Col. 2: alternative names. Col. 3: redshift. Col. 4: linear scale (kpc arcsec$^{-1}$) for our adopted cosmology. Col. 5: reference for redshift. Col. 6: reference for earlier observations of large-scale radio structure.

| Name          | Alternative | $z$  | kpc arcsec$^{-1}$ | Ref. |
|---------------|-------------|------|-------------------|------|
| NGC 193       | PKS 0036+03 | 0.0147 | 0.300             | 9    |
| UGC 408       |             |       |                   |      |
| 0206$+$35     | UGC 1651    | 0.0377 | 0.748             | 3    |
| 4C 35.03      |             |       |                   |      |
| 0755$+$37     | NGC 2484    | 0.0428 | 0.845             | 9    |
| M84           | 3C 272.1    | 0.0035 | 0.073             | 10   |
|              | NGC 4374    |       |                   |      |
| 3C 296        | NGC 5532    | 0.0247 | 0.498             | 7    |
| 0326$+$39     |             | 0.0243 | 0.490             | 7    |

References: 1, Bondi et al. (2000); 2, Bridle et al. (1991); 3, Falco et al. (1999); 4, Giacintucci et al. (2011); 5, Laing & Bridle (1987); 6, Laing et al. (2006b); 7, Miller et al. (2002); 8, Morganti et al. (1987); 9, Ogando et al. (2008); 10, Trager et al. (2000).

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**2 OBSERVATIONS AND DATA REDUCTION**

2.1 The sources

We selected four bright FR I sources for which the available data suggested (a) that full synthesis observations with the VLA would achieve a signal-to-noise ratio sufficient to image the linearly polarized emission from their counterjets with several beamwidths resolution transverse to the radio features, as required by our modelling methods, and (b) that the jets have formed lobe-like structures rather than diffuse outer plumes. Three of the sources, NGC 193, B2 0206$+$35 and B2 0755$+$37, are analogous to 3C 296 in having well-defined outer boundaries. The fourth, M84, is in some respects an intermediate case between the two classes, as we discuss below. We analysed a combination of new and archival data sets chosen to give good spatial-frequency coverage at two or three frequencies.

In addition, we improved our low-resolution images of 3C 296 (Laing et al. 2006b). Finally, we analysed shorter, low-resolution, archival VLA observations for B2 0326$+$39.

Alternative names, redshifts, linear scales and references for all of the sources are given in Table 1 (we drop the B2 from source names from now on). A journal of observations is given in Table 2.

2.2 VLA data reduction

The VLA data listed in Table 2 were calibrated and imaged using the AIPS software package, following standard procedures with a few additions. The flux-density scale was set using observations of 3C 286 or 3C 48 and (except for 0326$+$39) the zero-point of E-vector position angle was determined using 3C 286 or 3C 138, after correction for the instrumental leakage terms. The main deviations from standard methods were as follows.

First, we used the routine BLCAL to compute closure corrections for the 4.9-GHz observations. This was required to correct for large closure errors on baselines between EVLA and VLA antennas in observations from 2007 onwards (VLA Staff 2010), but it also improved a number of the earlier data sets. Whenever possible, we

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3 Laing et al. (2006b) give a full description of the observations of 3C 296; this is not repeated here.
Table 2. Journal of VLA observations. Col. 1: source name. Col. 2: VLA configuration. Col. 3: date of observation. Col. 4: centre frequencies for the one or two channels observed (MHz). Col. 5: bandwidth (MHz). Col. 6: the on-source integration time scaled to an array with all the 27 antennas operational. Col. 7: VLA proposed code.

| Source | Config- | Date       | \( \nu \) (MHz) | \( \Delta \nu \) (MHz) | \( t \) (min) | Proposed code |
|--------|---------|------------|-----------------|------------------------|-------------|---------------|
| NGC 193 | A | 2007 June 02 | 4885.1, 4835.1 | 50 | 280 | AL693 |
|        | A | 2007 June 28 | 4885.1, 4835.1 | 50 | 90 | AL693 |
|        | A | 2007 August 22 | 4885.1, 4835.1 | 50 | 41 | AL693 |
|        | A | 2007 August 23 | 4885.1, 4835.1 | 50 | 88 | AL693 |
|        | B | 2007 November 05 | 4885.1, 4835.1 | 50 | 318 | AL693 |
|        | B | 2007 November 16 | 4885.1, 4835.1 | 50 | 121 | AL693 |
|        | C | 2008 May 24 | 4885.1, 4835.1 | 50 | 223 | AL693 |
|        | D | 2007 March 11 | 4885.1, 4835.1 | 50 | 53 | AL693 |
|        | A | 2007 June 28 | 1365.0 | 25 | 83 | AL693 |
|        | A | 2007 August 22 | 1365.0 | 25 | 39 | AL693 |
|        | A | 2007 August 23 | 1365.0 | 25 | 97 | AL693 |
|        | B | 2007 November 16 | 1365.0 | 25 | 148 | AL693 |
|        | C | 2008 May 24 | 1365.0 | 25 | 61 | AL693 |
| 0206+35 | A | 2008 October 13 | 4885.1, 4835.1 | 50 | 486 | AL797 |
|        | A | 2008 October 18 | 4885.1, 4835.1 | 50 | 401 | AL797 |
|        | B | 2003 November 17 | 4885.1, 4835.1 | 50 | 254 | AL604 |
|        | C | 2004 March 20 | 4885.1, 4835.1 | 50 | 88 | AL604 |
|        | A | 2004 October 24 | 1385.1, 1464.9 | 25 | 189 | AL604 |
|        | B | 2003 November 17 | 1385.1, 1464.9 | 25 | 110 | AL604 |
| 0755+37 | A | 2008 October 05 | 4885.1, 4835.1 | 50 | 477 | AL797 |
|        | A | 2008 October 06 | 4885.1, 4835.1 | 50 | 383 | AL797 |
|        | B | 2003 November 15 | 4885.1, 4835.1 | 50 | 332 | AL604 |
|        | B | 2003 November 30 | 4885.1, 4835.1 | 50 | 169 | AL604 |
|        | C | 2004 March 20 | 4885.1, 4835.1 | 50 | 125 | AL604 |
|        | A | 1992 August 2 | 4885.1, 4835.1 | 50 | 55 | AM364 |
|        | A | 2004 October 25 | 1385.1, 1464.9 | 12.5 | 450 | AL604 |
|        | B | 2003 November 30 | 1385.1, 1464.9 | 12.5 | 160 | AL604 |
|        | C | 2004 March 20 | 1385.1, 1464.9 | 12.5 | 21 | AL604 |
| M84 | A | 1980 November 09 | 4885.1 | 50 | 223 | AL020 |
|        | A | 1988 November 23 | 4885.1, 4835.1 | 50 | 405 | AW228 |
|        | A | 2000 November 18 | 4885.1, 4835.1 | 50 | 565 | AW530 |
|        | B | 1981 June 25 | 4885.1 | 50 | 156 | AL020 |
|        | C | 1981 November 17 | 4885.1 | 50 | 286 | AL020 |
|        | C | 2000 June 04 | 4885.1, 4835.1 | 50 | 138 | AW530 |
|        | A | 1980 November 09 | 1413.0 | 25 | 86 | AL020 |
|        | B | 1981 June 25 | 1413.0 | 25 | 29 | AL020 |
| 0326+39 | D | 2000 February 09 | 1385.1, 1464.9 | 50 | 30 | AR402 |
|        | D | 1997 December 13 | 4885.1, 4835.1 | 50 | 11 | AR386 |
|        | D | 1997 December 16 | 4885.1, 4835.1 | 50 | 32 | AR386 |
|        | C | 1998 December 4 | 1464.9, 1414.9 | 50 | 11 | AR386 |
|        | D | 1997 December 13 | 1464.9, 1385.1 | 50 | 6 | AR386 |
|        | D | 1997 December 16 | 1464.9, 1385.1 | 50 | 9 | AR386 |

included observations of the bright, unresolved calibrator 3C 84 for this purpose; if it was not accessible during a particular observing run, we used 3C 286. We found that it was not adequate to use the standard calibration (which averages over scans) to compute the baseline corrections, as phase jumps during a calibrator scan caused serious errors in the derived corrections. We therefore self-calibrated the observations in amplitude and phase with a solution interval of 10 s before running BLCAL. We assumed a point-source model for 3C 84 and the well-determined CLEAN model supplied with the AIPS distribution for 3C 286.

Secondly, we imaged in multiple facets to cover the inner part of the primary beam at \( L \) band and to image confusing sources at large distances from the phase centre in all bands. Before combining configurations, we subtracted in the \((u, v)\) plane all sources outside a fixed central field. For 0755+37 at \( L \) band, this procedure failed to remove sidelobes at the centre of the field from a bright confusing source close to the half-power point of the primary beam. The reason is that the VLA primary beam is not azimuthally symmetric, so the effective complex gain for a distant source is not the same as that at the pointing centre and varies with time in a different way. We used the AIPS procedure PEELR to remove the offending source from the \((u, v)\) data for each configuration before combining them.

Finally, we corrected for variations in core flux density and amplitude scale between observations as described in Laing et al. (2006b). J2000 coordinates are used throughout this paper. If positions from archival data were originally in the B1950 system, then
Images used in spectral-index analysis, we integrated the flux. The observations of M84 in 1980 and 1981 used an earlier and less accurate value of the position of the phase calibrator B1236+077 (alias J1239+075) than that currently given in the VLA calibration manual. We have updated the astrometry to reflect the improved calibrator position. The archival L-band observations of M84 taken in 2000 used a pointing centre displaced by $\approx 1.1$ arcmin from the centre of the source.

The C-band data were usually taken in two adjacent 50-MHz frequency channels, which were imaged together. The L-band channels were also imaged together in $I$, in order to derive spectral-index images. For all sources except 0326+39, they were also imaged independently, primarily for the analysis of linear polarization.

In order to avoid the well-known problems introduced by the conventional clean algorithm for well-resolved, diffuse brightness distributions, total-intensity images at higher resolutions were produced using the multiscale clean algorithm as implemented in the AIPS package (Greisen, Spekkens & van Moorsel 2009) or, in one case, a maximum-entropy algorithm (Cornwell & Evans 1985, used as described by Leahy & Perley 1991). The standard single-resolution clean was found to be adequate for the lowest resolution $I$ images. Stokes $Q$ and $U$ images were CLEANed using one or more resolutions (we found few differences between single and multiple-resolution clean for these images, which have little power on large spatial scales). All of the images were corrected for the effects of the antenna primary beam.

In general, the deep 4.9-GHz images have off-source noise levels very close to those expected from thermal noise in the receivers alone. There are a few faint artefacts on the $I$ images. These are visible as concentric rings around the bright cores and, for NGC 193 at 1.35- and 1.6-arcsec resolution, a quadrupolar pattern at the 2$\sigma$ level. These are due to errors in the cross-calibration of the different array configurations, which were particularly troublesome due to the low declination of this source. The integrations for all of the L-band images and for the C-band image of 0326+39 are shorter and confusion from sources outside the field of view is worse, so noise levels are correspondingly higher.

Finally, we produced improved $I$ images from self-calibrated L- and X-band visibility data for 3C 296 (Laing et al. 2006b) using the multisresolution CLEAN algorithm.

As a check on the amplitude calibration and imaging of the $I$ images used in spectral-index analysis, we integrated the flux densities using the AIPS verb TVSTAT. We estimate that our errors are dominated by a residual scale error of $\approx 2$ per cent. All of the results are in excellent agreement with single-dish measurements (Table 3).

The configurations, resolutions, deconvolution algorithms and noise levels for the final images are listed in Table 3. The noise levels were measured before correction for the primary beam, and are appropriate for the centre of the field.

### 2.3 MERLIN observations and reduction

We also present MERLIN imaging in total intensity only for two of the sources. 0206+35 was observed for a total time of about 14 h. The array included the following telescopes: Defford, Cambridge, Knockin, Wardle, Darnhall, Mk2, Lovell and Tabley. The observations were carried out at 1420 MHz with a bandwidth of 15 MHz, in each of left and right circular polarizations. The nearby compact source 0201+365 was used as the phase calibrator and the flux-density scale was determined using 3C 286. The data were edited, corrected for elevation-dependent effects and non-closing errors, and flux-calibrated using the standard MERLIN analysis programs. Imaging and self-calibration were again performed using the AIPS package. The off-source image rms after self-calibration was close to that expected from receiver noise alone. The MERLIN observations of 0755+37 were described by Bondi et al. (2000).

The parameters of both the MERLIN images are given in Table 3.

### 3 IMAGES

#### 3.1 General

Our conventions for Figs 1–12 and the descriptions in the text are as follows.

(i) Images of total intensity, $I$, are shown as grey-scales, over ranges indicated by the labelled wedges. The units are mJy beam$^{-1}$.

(ii) We also show grey-scales of intensity gradient, $|\nabla I|$, approximated using a Sobel filter (Sobel & Feldman 1968).

(iii) We use the notation $P = (Q^2 + U^2)^{1/2}$ for polarized intensity and $p = P/I$ for the degree of linear polarization. $p_0$ is the degree of polarization at frequency $\nu$ (in GHz). All values of $P$ have been corrected for Ricean bias (Wardle & Kronberg 1974). Linear polarization is illustrated by plots in which vectors with lengths proportional to the degree of polarization at 4.9 GHz ($p_{0.9}$) and directions along the apparent magnetic field ($B_\perp$) are superposed on false-colour images of either $I$ (again with a labelled wedge indicating the range) or $|\nabla I|$. A value of $p = 1$ is indicated by the labelled bar. The apparent field direction is $\chi_0 + \pi/2$, where $\chi_0$ is the $E$-vector position angle corrected to zero-wavelength by fitting to the relation $\chi(\lambda^2) = \chi_0 + \Delta \chi = \chi_0 + R\chi \lambda^2$ for foreground Faraday rotation derived from the images in Table 3 (RM is the rotation measure). In some sources, we used RM images at a lower resolution to correct the position angles, as detailed in the captions. This procedure is valid if the RM varies smoothly over the low-resolution image, and maximizes the area over which we can determine the direction of the apparent field. Vectors are plotted where (a) $I \geq 5\sigma$, (b) $P \geq 3\sigma_p$ (the noise levels are given in Table 3) and (c) the RM is well determined. The RM images for 0206+35 and M84 were determined using three and four frequencies, respectively, and are shown in Guidetti et al. (2011); that for 0755+37 (also from three frequencies) will be described by Guidetti et al. (in preparation). For NGC 193, images were only available at 4.86 and 1.365 GHz. The integrated RM of the source is small ($\approx 18 \pm 2$ rad m$^{-2}$; Simard-Normandin, Kronberg & Button 1981) as are the variations of the position-angle difference across the source. We are therefore confident that a two-frequency RM determination is adequate in this case (the correction required to derive $B_\perp$ is in any case very small).

(iv) Spectral index, $\alpha$, is defined in the sense $S(\nu) \propto \nu^{-\alpha}$ and we use $\alpha_{1.4}$ for the index between frequencies $\nu_1$ and $\nu_2$ (in GHz). In the false-colour images of spectral index, the input $I$ images at the lower frequency are always blanked for $I < 3\sigma_I$. In cases where the areas over which emission was detected were essentially the same at both frequencies, we also blanked the higher-frequency image at $3\sigma_I$. If significant areas were detected only at the lower frequency, we

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4 The spectral-index image for M84 has additional blanking, as noted in the caption of Fig. 9(c).
did not blank the higher frequency image. Instead, we plot a single contour that indicates the boundary of the region where the source is detected at $f \geq 3 \sigma_I$ at the higher frequency. Outside this contour, the spectral indices are lower limits. We have carefully inspected the spectral-index images to check for edge effects and zero-level problems. We are confident that the values and lower limits in all of the unblanked regions are reliable except where explicitly stated and that the steep spectra seen at the edges of the lobes in several sources are real.

(v) The restoring beam (FWHM) is shown at the bottom of each plot.

(vi) We refer to the parts of the sources by the abbreviations N, S, E, W (for north, south, east, west) etc.

(vii) We refer to the main (brighter) and counter (fainter) jets.

3.2 NGC 193

Fig. 1(a) shows the total-intensity distribution over NGC 193 at 4.9 GHz and 4.05-arcsec FWHM resolution. The symmetrical jets appear to broaden rapidly and also bend away from their initial straight path as they reach the mid-points of symmetric lobes. The lobes both have well-defined leading edges that approximate arcs.
of circles in projection on the sky (the W lobe having a larger radius of curvature), but they lack hotspots that might mark the termination points of the jets. A broad, faint emission bridge fills the central region of the source between the lobes and appears to be wider than the lobes in the N–S direction at the centre of the source (similar to the ‘wings’ observed in some FR II sources; Cheung 2007, and references therein). Figs 1(b) and (c) taken together show that broad ‘caps’ of emission can be delineated in both the lobes by enhanced intensity gradients and by lower-than-average values of $\alpha_{4.9}$. The intensity gradients are largest at the outer edges of these caps, but there are also gradient features within the lobes (marked by arrows on Fig. 1b) which coincide with the edges of the flatter-spectrum region. The regions where the jets are most prominent have low spectral indices around 0.6. The spectral index at the trailing edges of the caps steepens smoothly to $\alpha \approx 0.9$ where the emission merges with the broader, symmetric lobes. The most diffuse lobe emission has spectral indices increasing from $\approx 1$ at the edges of the most elongated parts of the lobes to $\approx 1.4$ near the centre of the source, a spectral-index pattern characteristic of lobed radio sources of both the FR classes (see Section 4.2). There are regions of emission with spectral index approaching 2 at the edges of the faintest emission on the N and S edges of the source.$^5$

Fig. 1(d) shows that the distribution of the apparent magnetic field direction over the lobes is basically circumferential, while the magnetic field in the jets is perpendicular to the jets over most of their lengths. The structure of the apparent magnetic field in both the jets and the lobes appears regular, and characteristic of that commonly found in jets of FR I sources and in the lobes of both the FR classes.

Fig. 2(a) shows the total-intensity distribution over the jets at 4.9 GHz with a resolution of 1.6 arcsec FWHM. Both jets are fairly straight and similar in overall appearance, exhibiting rapid lateral expansion just beyond the distance from the unresolved nuclear radio source at which the E jet is markedly brighter than the W jet. Their edges are well delineated by steep transverse intensity gradients near the mid-point of the source (Fig. 2b). The surface brightnesses of both jets decrease smoothly with distance from the nucleus except at a distance of $\approx 25$ arcsec, where there are more

$^5$ The spectral index within a few arcsec N and S of the core is affected by artefacts in the 4.9-GHz image.
Figure 2. High-resolution images of the inner jets of NGC 193. (a) Total intensity at 4.9 GHz with 1.6 arcsec FWHM resolution. (b) Brightness gradient derived from the image in (a). Sharp steps in brightness (‘arcs’) are indicated. (c) Spectral index between 4.9 and 1.4 GHz at 1.6-arcsec resolution. The most prominent of the arcs, which shows a flattening in spectral index, is marked. (d) Vectors with directions along $B_a$ and magnitudes proportional to $p = 4.9$, plotted on false-colour images of total intensity at 4.9 GHz with 1.35 arcsec FWHM resolution. The vectors have been corrected for Faraday rotation using a 4.05-arcsec FWHM resolution RM image. (e) As in panel (d), but for the innermost jet regions at 0.45-arcsec resolution.
sudden drops, mostly clearly visible as ‘arcs’ crossing the jets on the gradient image (indicated in Fig. 2b). The overall spectral index of the jet-dominated emission appears to steepen with distance from the nucleus, but this is almost certainly the result of superposition of dimming jets on steeper-spectrum lobe emission. The prominent arc in the E jet is associated with a slight flattening in the spectrum (Fig. 2c).

Fig. 2(d) shows the intensity and apparent magnetic field distributions over the inner ≈45-arcsec regions of both jets at 1.35-arcsec resolution. The magnetic field organization over both jets is quite regular, with the field closest to the jet axis predominantly oriented perpendicular to the axis. The apparent field at the edges of the inner jets is parallel to the rapidly expanding outer isophotes. Farther from the nucleus, the edge field directions in both the jets converge towards the axis to form almost circular patterns.

Fig. 2(e) shows the 4.9-GHz total intensity and apparent magnetic-field distributions over the inner 15 arcsec (≈4.5 kpc) of the jets at 0.45-arcsec resolution. Both the jets exhibit faint inner regions in the first ≈2 arcsec from the nucleus before they brighten and subsequently flare. There is a bright, non-axisymmetric knot structure in the first ≈4 arcsec of the E jet, downstream of the flaring point (Laing et al. 1999), where both the jets brighten abruptly.

### 3.3 0206+35

Fig. 3 shows the total-intensity, brightness gradient, and spectral-index distributions over the whole of 0206+35 at two resolutions. Fig. 3(a), at 1.4 GHz and 4.5-arcsec FWHM resolution, shows that the large-scale structure consists of two lobes, overlapping and circular in cross-section, with well-defined outer edges to the NW and SE of the source, superimposed on fainter diffuse emission to the N and S. Fig. 3(b), at 4.9 GHz and 1.2-arcsec resolution, shows the source in more detail but with a reduced sensitivity to the largest scale emission. At this resolution, both the lobes show sharp outer boundaries. The roughly circular edge of the NW lobe protrudes beyond the diffuse emission, whereas the corresponding feature in the SE is well inside the outer boundary of the source and is most obvious in the E of the lobe, close to the termination of the jet. If the orientation of θ ≈ 40° determined for the inner jets (Laing & Bridle, in preparation) also applies to the lobes, then they

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**Figure 3.** Images of 0206+35. (a) Total intensity at 1.4 GHz with 4.5-arcsec FWHM resolution. (b) Total intensity at 4.9 GHz, 1.2-arcsec FWHM. (c) Intensity gradient at 1.4 GHz, 4.5-arcsec FWHM. (d) Intensity gradient at 1.4 GHz, 1.2-arcsec FWHM. The arrows mark the high brightness gradients around the inner boundary of the flat-spectrum cap. (e) Spectral index between 4.9 and 1.4 GHz, 4.5-arcsec FWHM. (f) Spectral index between 4.9 and 1.4 GHz, 1.2-arcsec FWHM. In panels (e) and (f), values outside the contours are lower limits.
are presumably ellipsoidal with an axial ratio $\approx 1.6$. Fig. 3(b) also shows some internal structure in both of the jets. The NW jet has the brighter base, and both bends and brightens as it enters its lobe, after which its path meanders. The SE counterjet appears to expand more rapidly initially, then also meanders as it enters its lobe.

Figs 3(c) and (d) show the 1.4-GHz intensity gradient images of 0206+35 at 4.5- and 1.2-arcsec resolution, respectively. The edges of the jets are clearly marked by enhanced intensity gradients at both resolutions, while significant internal structure is also apparent in the lobes. Both the lobes exhibit strong brightness gradients at their outer edges in these displays, corresponding to the sharp boundaries noted earlier. There is a particularly striking correlation between the main features of these intensity-gradient images and of the two 1.4–4.9-GHz spectral-index images shown as Figs 3(e) and (f). The emission inside the brightest intensity gradients around the jet has a lower spectral index, typically $<0.65$, than the $\approx 0.7–1.0$ spectral index that is prevalent over the rest of the lobes. The diffuse emission outside the lobes has spectral indices ranging from $\approx 1.05$ to $>2$, generally increasing with distance from the lobes towards the outer edge of the source. Also notable are the ‘fans’ of lower-spectral-index emission that can be traced from the ends of the jets to the regions at the edges of both the lobes that show the most pronounced brightness gradients. This is particularly striking in the NW lobe, where a cap of lower-spectral-index emission is bounded by the high brightness gradients marked by arrows on Fig. 3(d) and by the edge of the lobe. This suggests that the jet outflow has reached the end of the lobe in a less-collimated, but still identifiable, form. In the SE lobe, the jet bends to the N before appearing to impact the edge of the lobe at another enhanced brightness gradient, marked in Fig. 3(d).

Fig. 4 shows that the magnetic field configuration in both lobes is well ordered and basically circumferential, while the magnetic field in the jets is predominantly transverse on-axis, with evidence for a longitudinal component at the edges. The southern edge of the source is strongly polarized with field tangential to the boundary.

At 0.35-arcsec FHWM resolution (Fig. 5a) the lobe emission is substantially resolved out so the images are dominated by the jets. The bright base of the main (NW) jet is clearly centre-brightened, while the corresponding segment of the counterjet appears centre-darkened. While at first sight the main jet appears to expand more slowly than the counterjet, the geometry of the centre-darkened segment of the counterjet is very similar to that of the main jet over the first $\approx 10$ arcsec. This suggests a two-component view of these jets wherein a narrow inner structure, brighter to the NW and fainter to the SE, is seen superposed on a broader expanding structure that is slightly brighter to the SE than to the NW. We will interpret this elsewhere (Laing & Bridle, in preparation) as evidence for a symmetrical relativistic outflow surrounded by a mildly relativistic backflow in this source.

The magnetic field is clearly perpendicular to the jet axis over most of the length of both jets (Fig. 5b), but the first few arcsec of the main jet, where it is brightest, have the magnetic field parallel to the jet axis. There is also evidence for oblique, or parallel, magnetic field at the edges of both jets.

Fig. 5(c) shows the bright, narrow base of the NW jet from MERLIN data at 1.6 GHz. This higher resolution (0.16 arcsec FHWM) image unambiguously identifies the flaring point in the jet, 0.7 arcsec from the nucleus, where it brightens abruptly. This is an important fiducial distance for our modelling. The image also shows the start of rapid expansion downstream of the flaring point.
3.4 0755+37

Fig. 6 shows the total intensity, $|\nabla I|$ and $\alpha$ distributions over all of 0755+37 at two resolutions and the polarization at a low resolution. Fig. 6(a), at 1.4 GHz and 4.0-arcsec FWHM resolution, shows that the large-scale structure consists of two lobes, again roughly circular in projection, with well-defined but not particularly sharp outer edges to the W and E, plus fainter diffuse emission to the N and S. The E lobe has a series of narrow ridges and brightness steps, all roughly arcs of circles in projection, in the region where the brighter jet appears to terminate. They are recessed from the E boundary of this lobe and some may be the edges of thin shells. The structure of the W lobe is unusual, containing some arc-like features and other structure suggestive of a rapidly decollimating counterjet W of the nucleus, as previously described by Bondi et al. (2000), with a ‘hole’, or deficit of emission in the region where the counterjet might be expected to terminate. Fig. 6(b), at 4.9 GHz and 1.3-arcsec FWHM resolution, is insensitive to the largest scales of emission to the N and S of the main source, but clearly shows the internal structure in the E lobe, including the concentric semicircular ridges at the end of the jet (labelled on the figure). All of the substructure in the W lobe appears to be resolving out, though vestiges of the ridge apparent at lower resolution in Fig. 6(a) remain.

Figs 6(c) and (d) show the intensity gradients over the whole source at 1.4 GHz, 4.0-arcsec FWHM resolution and 4.9 GHz, 1.3 arcsec FWHM resolution, respectively. These figures emphasize the strong differences between the internal structures of the lobes: multiple recessed ridges with significant brightness gradients in the E lobe, but a much smoother structure in the W lobe away from the jet.

Figs 6(e) and (f) clearly show three distinct spectral-index regions on each side of the source, as follows.

(i) $\alpha \approx 0.6$ at the bases of both jets, in a broad cap in the NW part of the W lobe, and all along the region delineated by the strongest brightness gradients in the E jet.

(ii) $\alpha \approx 0.8$ over most of the rest of both lobes, including the ridge extending northwards from the nucleus.

(iii) There is also a steeper spectrum diffuse emission with $\alpha$ increasing from $\approx 1$ in the central part of the source to $\approx 1.5$ at the N and S edges.

The spectral-index image suggests that the counterjet flow persists as far as the ridge of emission in the W lobe marked on Figs 6(a) and (b), despite the lack of evidence for this in total intensity.

Fig. 6(g) shows that the apparent magnetic field in both of the lobes is exceptionally well organized, and mainly tangential to the lobe boundaries. The degree of linear polarization is $p \gtrsim 0.6$ over much of both the lobes, consistent with the high degree of organization evident from the vectors. Note the excellent alignment between the field vectors and the ridges of high brightness gradient on both sides of the source. Fig. 7 confirms the exceptional degree of ordering of the magnetic field in both the lobes at 1.3-arcsec FHWM resolution.

Fig. 8 shows that the jet bases on larger scales and at higher resolution. Fig. 8(a) is optimized to emphasize the fine-scale structure in the jets at 1.3-arcsec resolution. It shows that the E jet has the brighter base but becomes limb-brightened at the position indicated in Fig. 8(a) at about 18 arcsec from the nucleus. At this resolution, the W counterjet contains a centre-darkened structure that expands at about the same rate as the brighter E jet, embedded in a much broader, and more rapidly expanding cone of emission with at least two curved arcs (Fig. 8a). The centre of the counterjet is crossed by

Figure 5. (a) Grey-scale of the 4.9-GHz total-intensity distribution over the jets in 0206+35 at 0.35-arcsec FWHM resolution. The grey-scale range is 0–2.5 mJy beam$^{-1}$. (b) Vectors with lengths proportional to the degree of polarization at 4.9 GHz and directions along the apparent magnetic field, superimposed on a false-colour display of the total intensity at 4.9 GHz. The resolution is 0.35 arcsec FWHM. The vector directions are derived from three-frequency RM fits at 1.2-arcsec resolution. (c) Grey-scale of the 1.6-GHz total intensity distribution over the inner 5 arcsec of the NW jet and the unresolved nuclear source in 0206+35 at 0.16-arcsec FWHM resolution, from MERLIN. The grey-scale range is 0–5 mJy beam$^{-1}$. 
Figure 6. Images of the whole of 0755+37 at resolutions of 4.0 arcsec FWHM (panels a, c, e and g) and 1.3 arcsec FWHM (panels b, d and f). (a) Total intensity at 1.4 GHz. (b) Total intensity at 4.9 GHz. (c) Intensity gradient at 1.4 GHz. (d) Intensity gradient at 4.9 GHz. (e) and (f) spectral index between 4.9 and 1.4 GHz. (g) Vectors with lengths proportional to $p_{4.9}$ and directions along the apparent magnetic field from a three-frequency rotation-measure fit (Guidetti et al., in preparation), superimposed on the intensity gradient at 4.9 GHz.
Figure 7. Vectors with lengths proportional to the degree of polarization at 4.9 GHz and directions along the apparent magnetic field, superimposed on a false-colour display of the total intensity over 0755+37 at 4.9 GHz. The resolution is 1.3 arcsec FWHM and the colour-scale range is 0–2.5 mJy beam$^{-1}$. The vector directions are derived from three-frequency RM fits at 4.0-arcsec resolution (Guidetti et al., in preparation).

a prominent, straight bar of emission (labelled as such in Fig. 8a) at $\approx 15$ arcsec from the core. The steepest brightness gradients at the edges of both the jets are very similar in form within $\approx 15$ arcsec of the nucleus so that, as in 0206+35, the inner geometry of the counterjet structure appears to mimic that of the brighter jet on the other side of the source (Fig. 8b).

Fig. 8(b) also shows details of the magnetic field organization at the bases of both jets at 1.3-arcsec resolution. The bright base of the E jet has the magnetic field roughly parallel to the jet axis, but there is a rapid transition, with the field becoming perpendicular to the axis as the jet expands. On the counterjet side the field is also transverse. There is little evidence for any perturbation of the magnetic field structure at the edges of the jets except at the N edge of the counterjet where the magnetic field becomes parallel to the steepest brightness gradient once the jet widens significantly. The very high degree of polarization in the surrounding diffuse emission makes it difficult to disentangle the true polarization of the jets where their emission is weak, e.g. at their edges.

Figs 8(a) and (b) also show a filament of faint emission which extends for about 30 arcsec northwards from the vicinity of the nuclear source, roughly perpendicular to the jets. It has a very high degree of linear polarization, with an apparent magnetic field parallel to its length. Fig. 7 suggests that this highly polarized filament may be a part of a larger region of enhanced polarization that delineates the inner boundary of the W lobe.

Fig. 8(c) shows the total-intensity structures at the bases of the jets at 0.4-arcsec resolution. The main jet is clearly centre-brightened whereas the counterjet is not and the brighter edges of the counterjet lie mostly outside the region that would be delineated by reflecting the main jet across the nucleus. As in 0206+35 (Fig. 5a) there is a narrow collimated structure within which the main jet is systematically brighter than the counterjet, apparently superposed on a broader structure which is brighter around the counterjet than around the main jet. As for 0206+35, we will show elsewhere (Laing & Bridle, in preparation) that this structure can be modelled as a symmetrical relativistic outflow surrounded by a modestly relativistic backflow.

The polarization image in Fig. 8(d) shows the extent of the region at the bright base of the main jet in which the magnetic field at the edges is parallel to the expanding outer isophotes, whereas the on-axis field is oblique (see also Fig. 8b). Finally, a 1.7-GHz MERLIN image of the main jet base (Fig. 8e) shows the position of the flaring point and the details of the initial expansion.

3.5 M84

M84 is of particular interest for two reasons: it has a much lower radio luminosity than the other sources we have studied and it shows very clear evidence for interaction with the surrounding IGM (Finoguenov et al. 2008).

Fig. 9(a) shows the total-intensity distribution over M84 at 4.9 GHz with 1.65-arcsec FWHM resolution. Both the jets of this small (overall extent $\approx 12$ kpc), low-luminosity radio source expand rapidly and deflect within about 1 arcmin. They are surrounded by diffuse emission (at least in projection) everywhere except perhaps within a few arcsec of the nucleus. The initially brighter N jet can be traced as far as the edge of its lobe, where it bends through $\approx 90^\circ$ in projection and decollimates on impact. The bending is accompanied by strong brightness gradients (Fig. 9b). In contrast, and uniquely amongst the sources in this paper, the S jet (initially fainter and misaligned with the nucleus) appears to terminate within its lobe and to feed a bubble-like structure with significant internal brightness gradients and filaments. The bubble is contained within a smoother, more elongated structure, at least in projection. The spectral index between 1.4 and 4.9 GHz (Fig. 9c) is constant with $\alpha$ 6

Lower resolution (FWHM $\approx 4$ arcsec) radio observations, shown by Laing & Bridle (1987), are not reproduced here.
Figure 8. High-resolution images of the inner jets of 0755+37. (a) Total intensity at 4.9 GHz with 1.3-arcsec FWHM resolution, plotted with a compressed grey-scale range to emphasize fine-scale structure in and around the jets. (b) Vectors with lengths proportional to $p_{4.9}$ and directions along the apparent magnetic field superimposed on a false-colour image of intensity gradient at 4.9 GHz. The resolution is 1.3 arcsec FWHM. (c) Total intensity at 4.9 GHz, 0.4-arcsec FWHM. (d) Main jet base at 4.9 GHz with 0.4-arcsec FWHM resolution. $B_z$ vectors with lengths proportional to $p_{4.9}$ are superposed on a false-colour plot of total intensity. (e) MERLIN image of the main jet base at 1.7 GHz with 0.16-arcsec FWHM resolution (Bondi et al. 2000). Corrections for Faraday rotation in panels (b) and (d) were made using a three-frequency RM fit at 4.05-arcsec resolution (Guidetti et al., in preparation).
Figure 9. Images of M84 at 1.65-arcsec FWHM resolution. (a) 4.9-GHz total intensity. (b) 4.9-GHz intensity gradient. (c) Spectral index between 1.4 and 4.9 GHz, plotted only where its rms error is <0.1. The vertical ‘streaks’ are artefacts. Arrows mark the areas where the spectral index is significantly steeper than the typical value of $\alpha = 0.6$. (d) $B_\parallel$ vectors with lengths proportional to $p_{220}$, superposed on a false-colour plot of intensity gradient. Corrections for Faraday rotation were made using a four-frequency RM image at 4.5-arcsec resolution (Guidetti et al. 2011). All panels show identical areas.
Fig. 10. 4.9-GHz images of M84 at 0.4-arcsec FWHM resolution. (a) Total intensity for the whole source. (b) Total intensity for the jets. (c) Intensity gradient for the jets. Three prominent 'arcs' in the N jet are labelled on panels (b) and (c). (d) Total intensity for the inner jets, showing the abrupt bend in the counterjet. (e) $B_x$ vectors with lengths proportional to $p_{4.9}$, superimposed on a false-colour image of intensity gradient for the N jet. (f) As (e), but for the S jet.

$\approx 0.6$ over the jets, within the southern bubble and over most of the N lobe. The only regions of significantly steeper spectral index that we have detected (marked by arrows on Fig. 9c) are on both sides of the south jet base and to the west of the north jet. The current observations are too noisy to determine the spectral index in the low-surface-brightness emission outside the southern bubble. Fig. 9(d) shows the apparent magnetic field structure over the whole source at 1.65-arcsec FHWM resolution. The magnetic field in the S lobe
Figure 11. (a) Grey-scale of the 1.4-GHz total intensity over 3C 296 at 5.5-arcsec FWHM resolution. (b) Intensity gradient image at the same frequency and resolution as panel (a). (c) False-colour plot of the 1.4–4.9 GHz spectral index distribution at 5.5-arcsec FWHM resolution; data plotted outside the white contour are lower limits.

Figure 12. (a) Grey-scale of the 1.4-GHz total intensity over 0326+39 at 18-arcsec FWHM resolution. (b) False-colour plot of the spectral index ($\alpha_{4.9}^{1.4}$) distribution at the same resolution.

is broadly circumferential and appears well aligned with the peak in the brightness gradient at the edge of the bubble. There is a sudden increase in the degree of polarization at the edge of the bubble, suggesting a discontinuity in the field structure at that location. A configuration in which the field is confined to ellipsoidal shells but is otherwise random (model A of Laing 1980) gives qualitatively the correct polarization distribution, but the predicted variation of $p$ across the lobe is smoother than we observe. The magnetic field in the N lobe is predominantly perpendicular to the presumed path of the jet along its mid-line.

Fig. 10(a) shows the 4.9-GHz total-intensity distribution over the whole source at 0.4-arcsec FWHM resolution. This highlights the filamentary structure in the N lobe, the S bubble and a thin rim of emission around the S lobe. The intensity and gradient images of the jets at this resolution (Figs 10b and c) emphasize the edges of both jets and the curved arcs in the north. The former also shows a curious thin feature (labelled A) joining the S jet and the edge of its lobe. The misalignment (non-collinearity) of the axes of the N and S jets beyond a few arcsec (a few hundred parsecs) from the nucleus and the initially knotty structure of the N jet, can be seen on a larger scale in Fig. 10(d), which also shows faint emission close to the nucleus on both sides.

Figs 10(e) and (f) show that, although the apparent magnetic field in the jets is locally well organized, there are significant regions where the field is oblique to the jet axis. In the outer parts of both
jets the field appears to be predominantly transverse, but the jet emission also becomes blended with that from the lobes. M84 may be an intermediate case between lobed and tailed sources, showing some characteristics of each class. The N jet terminates in a sharp bend at the outer edge of its lobe, as often seen in lobed sources (e.g. 3C 296, Section 3.6), but there are hints of a nascent tail structure in the NE. This is supported by Chandra imaging of M84 (Finoguenov et al. 2008), which suggests that the NE lobe is breaking out of the surrounding hot plasma. In contrast, the S jet terminates well within its bubble-like lobe. The oscillation of the S jet prior to its eventual disruption is strongly reminiscent of that of the jets within the S spurs of the tailed sources 3C 31 and 3C 449 (Laing et al. 2008; Katz-Stone & Rudnick 1997). The spectral gradients (such as they are) are more characteristic of lobed sources, with no hint of steepening outwards. The constancy of the spectral index across the radio structure is not surprising: given the small (∼12-kpc) size of the source, synchrotron losses are unlikely to have had enough time to steepen the spectrum at GHz frequencies even in the more extended regions.

3.6 3C 296

Fig. 11 shows the 1.4-GHz total intensity and brightness gradient together with the 1.4–4.9-GHz spectral index distributions over 3C 296 at 5.5-arcsec resolution. The intensity data are essentially those in figs 1(a) and 4(a) of Laing et al. (2006b) with an improved deconvolution, but the grey-scale range in Fig. 11(a) is chosen to show the jets more clearly where they appear to enter the lobes. The corresponding intensity gradient is shown in Fig. 11(b). Lower limits to the spectral indices have been plotted outside the white intensity contour in Fig. 11(c) to provide a better representation of the large-scale spectral gradients at the edges of the radio source. There is clear evidence that the flatter spectrum (α ≈ 0.5–0.65) jets propagate to the edges of both the lobes, where they deflect and eventually blend with more extended steeper-spectrum emission whose spectral index α ≈ 1. The NE jet forms a cap of flat-spectrum emission with a semicircular outer boundary, again marked by sharp brightness gradients. The flow (as traced by its flatter spectrum) then turns through ≈140° in projection, crosses the entire lobe and impacts on the boundary at the position marked in Fig. 11(b). The SW jet, on the other hand, does not form a cap, but appears to make an oblique impact on the wall of the lobe before turning through almost 180° in projection back towards the nucleus. The spectral index of the more extended emission increases further towards the centre of the source and towards its outer edges, where α ≈ 2.

3.7 0326+39

Fig. 12 shows the distributions of the 1.4-GHz total intensity and 1.4–4.9-GHz spectral index over 0326+39 at 18-arcsec FWHM resolution. As in the other sources studied here, the lobes of 0326+39 appear to surround the jets in projection. Even at this relatively low resolution, the jets are clearly traceable to the outer parts of the lobes in both total intensity, where they appear to twist and deflect close to the outer edges of the lobes, and spectral index. The W jet exhibits a particularly strong kink towards the S about 2 arcmin (∼60 kpc) from the nucleus; this kink is clearly replicated in the spectral index distribution.

The extended emission of both the lobes also shows a well-defined spectral index gradient, increasing towards the nucleus from α ≈ 1 near the broad caps that appear to be dominated by the outer jet emission to a significantly steeper spectrum with α ≈ 2 near the centre of the source. The spectral index also appears to increase towards α ≈ 2 in the outer part of the faint southward extension of the E lobe.

4 DISCUSSION

4.1 Initial jet propagation

There appear to be few, if any, morphological differences between the jet base regions in lobed and tailed FR I sources, whose common properties include the following.

(i) The initial rapid expansion (flaring) and recollimation of the jets is essentially identical in both types of FR I source.

(ii) Jet bases usually show significant side-to-side asymmetries, although a few very symmetrical examples of each type are known.

(iii) With the exception of these symmetrical cases, there are further common properties, as follows:

(a) One jet in each source exhibits a bright region at its base, often with non-axisymmetric knots and a predominantly longitudinal magnetic field.

(b) Jet brightness and polarization asymmetries are correlated: the apparent magnetic field on-axis in the brighter jets is initially longitudinal, but switches to transverse at larger distances; this in the fainter jets is always transverse.

(c) The jet/counterjet ratio falls with increasing distance from the nucleus.

These regions at the bases of FR I jets are also those in which our models (Laing & Bridle 2002a; Canvin & Laing 2004; Canvin et al. 2005; Laing et al. 2006b) show that the jets decelerate from relativistic to subrelativistic velocities. The development of a transverse velocity gradient across the jets implies that they decelerate primarily by boundary-layer entrainment of the external medium. We suggest that this entrainment occurs primarily in the dense, kpc-scale corona of hot plasma that surround the nuclei of twin-jet radio galaxies (probably with an additional contribution from stellar mass-loss) and that the entrainment effectively turns off on large scales, as it must to avoid further decollimation. Chandra observations have revealed coronae of this type in 0206+35, 0755+37 (Worrall, Birkinshaw & Hardcastle 2001), 0326+39 (Hardcastle, private communication), M84 (Finoguenov et al. 2008) and 3C 296 (Hardcastle et al. 2005; Croston et al. 2008); NGC 193 may have a similar component (Giacintucci et al. 2011). The coronae for which data are available have central electron densities of 10^5 to 7 × 10^7 m^{-3}, central pressures of 3 × 10^{-11} to 4 × 10^{-10} N m^{-2} and core radii of 0.3–2 kpc. It seems likely that lobe plasma is excluded from the immediate vicinity of the nucleus by the high-pressure coronae, so the jets in both types of source initially propagate in essentially identical environments, unshielded from the IGM. Further evolution of the jets will depend on their surroundings: if they propagate through low-density lobe material, then entrainment will effectively cease and they will recollimate to become almost cylindrical flows, as seen in the sources described here. Entrainment rates are also likely to be small in jets without surrounding lobes provided that the external density is low. For example, there is no sign of any lobe surrounding the inner jets of NGC 315, yet it has a very small opening angle after recollimation (Canvin et al. 2005). This argues for a negligible entrainment rate at distances ≥ 35 kpc, and the external density does indeed fall rapidly on these scales (Croston et al. 2008). In contrast, we have argued that entrainment continues at a lower, but still significant rate after recollimation...
in 3C 31, whose inner jets also have no surrounding lobes. In this source, the opening angle after recollimation is larger, our models indicate continuing deceleration and there is a hot-gas component with a large core radius in addition to the inner corona (Laing & Bridle 2002b).

One feature of jet propagation appears to be unique to lobed sources, however. Our high-resolution data for 0206+35 and 0755+37 show that the apparent difference in opening angle between the main and counterjets seen at lower resolution in these sources is a manifestation of a two-component jet structure. In both the sources, the main jet and the counterjet appear to contain both narrow (well-collimated) and broader features on both sides of the nucleus, but the better collimated parts of the main jet are centre-brightened while those in the counterjet are centre-darkened. The broader features at the edges of the counterjets are also slightly brighter than those of the main jets. What appears to be poorer collimation of the counterjet at low resolution is now seen as a narrow centre-brightened jet opposite a similarly narrow centre-darkened counterjet, surrounded by broader emission which is slightly brighter around the counterjet than around the main jet. We will explore explanations for this ‘two-component’ jet structure in terms of relativistic outflow in the well-collimated component surrounded by mildly relativistic backflow in the broader component in a later paper (Laing & Bridle, in preparation).

4.2 Jet termination and lobe structure

With the partial exception of M84, to which we return at the end of this section, the sources described in this paper have lobes similar to those in FR II sources (e.g. Alexander & Leahy 1987; Carilli et al. 1991; Kharb et al. 2008). They exhibit sharp brightness gradients at their outer edges, spectral indices that steepen towards the nucleus from the outer lobes and away from the source axis, off-axis wings of diffuse emission near their centres, and generally circumferential magnetic fields. The only obvious difference from the lobes of FR II sources is the evident lack of hotspots at the ends of the FR I jets. Similar spectral gradients occur in a larger sample of lobed FR I sources observed at lower resolution (Parma et al. 1999). Where the jets dominate the total intensity, they all have similar spectral indices in the range 0.5–0.7. Even when the jets are not obviously dominant in intensity alone, the observed spectral index distributions can trace plausible paths for jets towards the edges of the lobes. This spectral signature implies that steeper-spectrum lobe material has been displaced by flatter-spectrum jet material along an extended pathway through the lobes. Note that the spatial resolution of our data relative to the overall source size is higher than for most published multifrequency imaging of sources in either FR class. Together with the ability to trace the jet flow via its flatter spectrum and the use of intensity gradient images to indicate enhanced compression, this has allowed us to identify a number of new types of structures in the lobes.

The jets often terminate in what we have called ‘caps’, with the following properties.

(i) They typically occur at the ends of lobes (one example, 0755+37SE, appears recessed, perhaps as a result of projection) and are clearly associated with jet termination.

(ii) They are bounded at their leading edges by smooth outer isophotes (approximated by segments of circles) with sharp intensity gradients.

(iii) They also have inner boundaries, again marked by high intensity gradients.

(iv) Their emission has a flat spectrum, close to that typical of jets ($\alpha \approx 0.6$) after accounting for contamination by steeper-spectrum diffuse emission.

(v) Four out of five examples are fairly symmetrical with respect to the local jet axis. The exception is 3C 296NE.

There are five clear cases of such ‘caps’ out of the 10 FR I lobes we have studied at high resolution: NGC 1938 and W, 0206+35NW, 0755+37SE and 3C 296NE. 0755+37NW may well be similar.

Other jet terminations show some, but not all, of the same features. In particular, several show enhanced brightness gradients, but without obvious inner boundaries. In 0206+35SE, the jet bends away from its initial direction and creates a sharp brightness gradient where it impacts on the side of the lobe; the associated emission again has a relatively flat spectrum. Both lobes of 0326+39 probably have similar structures, but the available resolution is not yet high enough to be sure. In 3C 296SW and M84N, the jets remain straight until they make oblique impacts on the lobe walls at locations marked by high intensity gradients after which they bend abruptly. The former case also shows flatter-spectrum emission at the impact point. 0755+37NW has a weak ring of emission surrounding a flatter spectrum region, but this is contained entirely within the outline of the lobe. It is possible that some of these structures (especially the last) are caps seen from an unfavourable angle.

We see little convincing evidence for enhancements in $|V_1|$ crossing the jets close to their termination points, such as might be expected of strong shocks. This implies that the flow is internally subsonic or transonic. Our estimates of the on-axis flow velocities after the initial rapid deceleration range from $\lesssim 0.1c$ to $\approx 0.6c$, compared to an internal sound speed of $3^{-1/2}c \approx 0.58c$ for an ultrarelativistic plasma. Unless there is significant deceleration on scales larger than our model, the implication is that the jets must be very light and energetically dominated by relativistic particles and magnetic field.

The lobes in this class of source are very different from the subsonic, buoyant plumes which are thought to form the outer structures of large FR I sources like 3C 31 (Laing et al. 2008). The picture that emerges for jet termination in lobed FR I sources is that the flow can be traced at least as far as the end of the lobe via its flatter spectrum. Where it impacts on the lobe surface, a high-pressure region (the cap) can be created. The smooth shape of the outer isophotes (compared to the more ragged outline of the lobes) suggests that the forward expansion is at least mildly supersonic with respect to the external medium. Jet material flows through the cap and back into the lobe, eventually mixing with pre-existing lobe plasma. The flow pattern is sometimes consistent with axisymmetry (or at least appears so in projection) but can bend by large angles without completely losing its collimation. The clearest example is 3C 296NE, where the flow bends by $\approx 140^\circ$ in the plane of the sky and can be traced at least as far as the trailing edge of the lobe, where its impact is marked by a sharp brightness gradient. An alternative to the formation of a cap appears to be an oblique collision with the boundary of the lobe. In at least one case, 0206+35SE, the jet deflects from its original straight path before hitting the edge of the lobe. This raises the possibility that the impact point moves around the surface of the lobe, extending it in different directions at different times and lowering the average advance speed of the lobe compared with the instantaneous speed of the impact point, as in the ‘dentist’s drill’ model of FR II sources (Scheuer 1982).

As noted in Section 3.5, M84 appears to be an intermediate case, in which only one of the jets appears to impact on its lobe.
boundary, but no tails have (yet) developed. The S lobe of M84 is morphologically very similar to the spurs in 3C 31, albeit on a much smaller linear scale. This adds to the developing picture of the transition between fast, well-collimated jets and slow plumes in tailored FR I sources, which is often a two-stage process. The jets first enter bubbles, within which they disrupt, often thrashing around (as in M84S) before disintegrating completely. The tails are then formed by escape of material from the bubbles along the direction of the steepest pressure gradient rather than directly from the jet flow. A similar morphology is often found in wide-angle tail sources (Hardcastle & Sakelliou 2004).

5 SUMMARY

We have presented deep, high-resolution, multiconfiguration VLA imaging of four FR I radio sources, NGC 193, 0206+35, 0755+37 and M84, together with lower resolution observations of 0326+35, 0755+37 and M84, and a re-analysis of our published images of 3C 296. These sources are all examples of ‘lobed’ FR I radio galaxies. Our results, displayed as images of total intensity, brightness gradient, degree of polarization, apparent magnetic-field direction and spectral index, show common features, as follows.

(i) All of the sources have twin radio jets, with side-to-side brightness ratios decreasing with distance from the nucleus in a manner qualitatively consistent with relativistic, decelerating flow.

(ii) The brightness and polarization distributions of the inner jets are very much like those in tailored radio sources, indicating similar deceleration physics. We suggest that the jets in both classes of source propagate unshielded from the surrounding IGM within dense, kpc-scale coronae, leading to efficient boundary-layer entrainment.

(iii) Farther from the nucleus, the jets in both classes of source recollimate. This implies that the entrainment rate is low whether or not they are surrounded by lobe plasma.

(iv) 0206+35 and 0755+37 show evidence for a two-component jet structure in which a centre-brightened main jet and centre-darkened counterjet are surrounded by broader features that are somewhat brighter on the counterjet side, suggesting that a central relativistic outflow is surrounded by a slower, but still mildly relativistic, backflow.

(v) In all but one case (M84S), the jets propagate to the ends of their lobes. A continuing, but less well collimated, flow can often be traced in spectral index or brightness gradient images.

(vi) Five or six of the 10 jets we have studied at high resolution terminate at the ends of their lobes in features we call ‘caps’ with smooth outer isophotes, sharp inner and outer intensity gradients and relatively flat spectra.

(vii) An additional three out of 10 jet terminations are best described as oblique collisions of jets with the outer lobe walls: they also show enhanced outer intensity gradients and flat spectra and may be caps seen at unfavourable angles.

(viii) The lobes resemble those in FR II sources, with sharp outer brightness gradients, spectral indices that steepen towards the nucleus and circumferential apparent magnetic fields.

(ix) There is little evidence for features in the jet brightness distributions which can be identified as strong shocks, either at recollimation or where they terminate. This implies that the flow is internally subsonic or transonic on large scales.

We will present quantitative modelling of the inner jets in later papers.

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