VLBA AND CHANDRA OBSERVATIONS OF JETS IN FRI RADIO GALAXIES: CONSTRAINTS ON JET EVOLUTION

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ABSTRACT

We present here the results from new Very Long Baseline Array (VLBA) observations at 1.6 and 5 GHz of 19 galaxies of a complete sample of 21 Uppsala General Catalog (UGC) Fanaroff–Riley type I (FRI) radio galaxies. New Chandra data of two sources, viz., UGC 00408 and UGC 08433, are combined with the Chandra archival data of 13 sources. The 5 GHz observations of 10 “core-jet” sources are polarization-sensitive, while the 1.6 GHz observations constitute second-epoch total intensity observations of nine “core-only” sources. Polarized emission is detected in the jets of seven sources at 5 GHz, but the cores are essentially unpolarized, except in M87. Polarization is detected at the jet edges in several sources, and the inferred magnetic field is primarily aligned with the jet direction. This could be indicative of magnetic field “shearing” due to jet-medium interaction, or the presence of helical magnetic fields. The jet peak intensity I, falls with distance d from the core, following the relation, I, ∝ d−4, where a is typically ∼ −1.5. Assuming that adiabatic expansion losses are primarily responsible for the jet intensity “dimming,” two limiting cases are considered: (1) the jet has a constant speed on parsec scales and is expanding gradually such that the jet radius r ∝ d0.4; this expansion is, however, unobservable in the laterally unresolved jets at 5 GHz, and (2) the jet is cylindrical and is accelerating on parsec scales. Accelerating parsec-scale jets are consistent with the phenomenon of “magnetic driving” in Poynting-flux-dominated jets. While slow jet expansion as predicted by case (1) is indeed observed in a few sources from the literature that are resolved laterally, on scales of tens or hundreds of parsecs, case (2) cannot be ruled out in the present data, provided the jets become conical on scales larger than those probed by VLBA. Chandra observations of 15 UGC FRIs detect X-ray jets in 9 of them. The high frequency of occurrence of X-ray jets in this complete sample suggests that they are a signature of a ubiquitous process in FRI jets. It appears that the FRI jets start out relativistically on parsec scales but decelerate on kiloparsec scales, with the X-ray emission revealing the sites of bulk deceleration and particle reacceleration.

Keywords: galaxies: active – galaxies: jets – polarization – radio continuum: galaxies – techniques: interferometric – X-rays: individuals (UGC00408, UGC08433)

Online-only material: color figure

1. INTRODUCTION

It is now widely believed that the enormous energy output from an active galactic nucleus (AGN) is the result of mass accretion onto a supermassive black hole. A small fraction of AGNs have powerful bipolar radio outflows extending to intergalactic distances. These “radio-loud” AGNs fall primarily into two morphological classes: the relatively low-power Fanaroff–Riley type I (FRI; Fanaroff & Riley 1974) radio galaxies possess broad jets that flare out into radio lobes, while the high-power FRII radio galaxies exhibit narrow, collimated jets that terminate in hot spots, with the backflowing plasma forming the radio lobes. As AGN jets experience bulk relativistic motion, which gives rise to Doppler favoritism, and most have axisymmetric tori-like obscuring structures (though perhaps not all, e.g., FRI galaxies—Chiaberge et al. 1999 and Kharb & Shastri 2004), which hide their central regions from certain lines of sight, their orientation in the sky plays a dominant role in their appearance. On the basis of orientation-independent properties like extended radio emission, emission line spectra, host galaxy type, and galaxy environment, a simple Unified Scheme has emerged (e.g., Urry & Padovani 1995), according to which the BL Lac objects and radio-loud quasars are the relativistically beamed counterparts of FRI and FRII radio galaxies, respectively (however, see Singal 1996; Kharb et al. 2010).

It has been suggested that the jets in both classes start out relativistically (e.g., Giovannini et al. 2001), but the FRI jets decelerate on scales of about a kiloparsec from the core (e.g., Laing et al. 1999). The aim of this paper is to explore the scales at which FRI jets decelerate through parsec-scale total intensity and polarimetric observations with the Very Long Baseline Array (VLBA) and kiloparsec-scale X-ray observations with the Chandra X-ray Observatory.

1.1. UGC Sample and Previous Work

In order to investigate the nuclear environment and jet physics of low-power radio galaxies, we have been conducting a large multi-wavelength study of a well-defined complete sample of 21 FRI radio galaxies from the Uppasala General Catalog (UGC) of galaxies (Table 1). The selection criteria are: (1) Hubble type E or S0; (2) recession velocity <7000 km s−1 (z < 0.0229); (3) optical major axis diameter >1; (4) total flux density at 1.4 GHz, S1.4 > 150 mJy; (5) declination −5° < δ < 82°; (6) black hole...
rather than starburst source from the IRAS\(^7\)/radio flux ratio; and (7) radio size >10\(^\prime\) in Very Large Array (VLA) images at 1.49 GHz with 2\(^\prime\) resolution, where the size is measured at contours of 3\(\sigma\) (Condon & Broderick 1988). The sample covers two magnitudes in absolute blue luminosity and about 80 in radio power.

The host galaxies have been studied by Verdoes Kleijn et al. (1999, 2002) using the Wide-Field Planetary Camera 2 (WFPC2) on board the Hubble Space Telescope (HST), while the gas dynamics and black hole masses have been studied by Noel-Storr et al. (2003) using the Space Telescope Imaging Spectrograph on HST. As the selection criteria specify a constraint on the total radio luminosity, which is typically dominated by the kiloparsec-scale lobe structure, the sample is unbiased in radio core luminosity.

The 1.6 GHz VLBA–VLA study of the radio structure in 17 UGC galaxies was carried out by Xu et al. (2000). The four sources that were not included in the study were the well-studied source UCG 07654 (M87), UGC 6635 which did not have a VLA core, and UGC 07115 and UGC 12064, which were included later on in the sample, UGC 06635 which lacked a VLA core, and UGC 12531 which was only tentatively classified as a “core–jet” source by Xu et al. (2000).

Fifteen sample UGC galaxies have also been studied with the Chandra X-ray Observatory. Nine of these fifteen sources exhibit X-ray jets in them. We present here new Chandra X-ray images of two sample FRI radio galaxies, viz., UGC 00408 and UGC 08433.

The paper is structured as follows. Sections 2 and 3 describe the radio and X-ray observations, and data analysis and results, respectively. The discussion follows in Section 4, while Section 5 presents the summary and conclusions from this study. The spectral index \(\alpha\) is defined such that flux density at frequency \(f\) is, \(S_f \propto f^{-\alpha}\) and the photon index \(\Gamma = 1 + \alpha\).

Throughout this paper, we adopt the cosmology in which \(H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}\), \(\Omega_m = 0.27\), and \(\Omega_{\Lambda} = 0.73\).

| Source Name | Other Names | Galaxy Type | R.A. (hr m s) | Decl. (\(^\prime\)\(^\prime\)\(^.\)\(^.\)) | Redshift | Scale (pc mas\(^{-1}\)) |
|-------------|-------------|-------------|---------------|-----------------|----------|------------------|
| UGC 00408   | NGC 193     | S0          | 00 39 18.5829 | +03 19 52.584   | 0.014657 | 0.274            |
| UGC 00597   | NGC 315     | E           | 00 57 48.8834 | +30 21 08.812   | 0.016485 | 0.311            |
| UGC 00689   | 3C 31, NGC 383 | E0         | 01 07 24.9593 | +32 24 45.237   | 0.017005 | 0.322            |
| UGC 01004   | NGC 541     | E           | 01 25 44.3078 | −01 22 46.522   | 0.018086 | 0.343            |
| UGC 01413   | NGC 741     | E           | 01 56 20.9902 | +05 37 44.277   | 0.018549 | 0.353            |
| UGC 01841   | 3C 66B      | E-S0        | 02 23 11.4073 | +42 59 31.403   | 0.021258 | 0.411            |
| UGC 03695   | NGC 2329    | E-S0        | 07 09 08.0061 | +48 36 55.733   | 0.019330 | 0.392            |
| UGC 05073   | NGC 2892    | E           | 09 32 52.9316 | +67 37 02.630   | 0.022822 | 0.460            |
| UGC 06635   | NGC 3801    | E           | 11 40 17.31   | +17 43 36.8     | 0.011064 | 0.246            |
| UGC 06723   | 3C 264, NGC 3862 | E       | 11 45 05.0099 | +19 36 22.756   | 0.021718 | 0.455            |
| UGC 07115   | MCG 04-29-031 | E         | 12 08 05.81   | +25 14 16.4     | 0.022602 | 0.470            |
| UGC 07360   | 3C 270, NGC 4261 | E        | 12 19 23.2162 | +10 49 29.702   | 0.007465 | 0.175            |
| UGC 07455   | NGC 4335    | E           | 12 23 01.8881 | +58 26 40.384   | 0.014517 | 0.320            |
| UGC 07494   | M84, 3C 272.1, NGC 4374 | S0        | 12 25 03.7433 | +12 53 13.143   | 0.003536 | 0.095            |
| UGC 07654   | M87, 3C 274, NGC 4486 | E        | 12 30 49.4234 | +12 23 28.044   | 0.004360 | 0.111            |
| UGC 08149   | NGC 5127    | E           | 13 23 45.0156 | +31 33 56.703   | 0.015951 | 0.342            |
| UGC 08333   | NGC 5141    | S0          | 13 24 51.4403 | +36 22 42.763   | 0.017379 | 0.363            |
| UGC 09058   | NGC 5490    | E           | 14 09 57.2984 | +17 32 43.911   | 0.016195 | 0.341            |
| UGC 11718   | NGC 7052    | E           | 21 18 33.046  | +26 26 49.251   | 0.015584 | 0.293            |
| UGC 12064   | 3C 449      | E-S0        | 22 31 21.35   | +39 21 33.2     | 0.017065 | 0.324            |
| UGC 12531   | NGC 7626    | E           | 23 20 42.5391 | +08 13 00.992   | 0.011358 | 0.205            |

\(^7\) Infrared Astronomical Satellite.
all the observations, two intermediate frequency channels with a bandwidth of 8 MHz each, were used.

The data were reduced and self-calibrated using standard reduction and imaging procedures in the Astronomical Image Processing System (AIPS). The standard steps included fixing the data, applying ionospheric corrections, applying the Earth orientation parameters (EOPs), amplitude calibration, and phase calibration. Los Alamos was used as the reference antenna at all stages of the calibration for the 5 GHz data. In addition, amplitude corrections were made using the AIPS task APCAL, while phase corrections for parallel and cross-correlated data were made using the task FRING. For the 1.6 GHz data, the instrumental phase corrections were determined using pulse-cals for all but one data set, viz., for the phase-reference calibrator J0155+0438 and the target source UGC 01413. For this one case, we had to use a small subset of the data for fringe fitting to determine the optimal solutions. In addition, Kitt Peak was used as the reference antenna except in three cases where alternate antenna had to be chosen (viz., UGC 01004—Pie Town; UGC 01413 and UGC 06635—Los Alamos). The instrumental corrections were then applied to the entire data set using global fringe fitting.

For the 5 GHz data, the instrumental polarization leakage term calibrator was J1407+2827, while the electric vector position angle (EVPA) calibrator was J1310+3220. The AIPS task LPCAL was used to obtain the antenna D-terms for this calibrator, which were then transferred to the main data set. The EVPA calibrator and its position angle in the VLA monitoring program close to the time of the VLBA observation was used to determine the absolute EVPA. The EVPA in the VLA monitoring is assumed to be close to the intrinsic value and the difference between the VLA and the VLBA EVPAs is assumed to be due to instrumental effects which can then be compensated. Specifically, the VLA EVPA information existed for 2003 February 8 and 2003 March 5. Assuming a linear EVPA–date relation, we obtained the EVPA for the observing dates (2003 February 7 and 14) via a simple interpolation. The VLBA EVPA was obtained from the polarized regions in the Stokes’ Q and U maps of J1310+3220, following the relation \[ \chi = (1/2) \tan^{-1}(U/Q). \] The phase-reference calibrators were then separated from the main data set using the task SPLIT.

The AIPS tasks IMAGR and CALIB were used iteratively for imaging and self-calibration. The solutions from the final converged images of the phase calibrators were transferred to the targets.

Significant discrepancies were observed in the positions of seven targets at 5 GHz. The discrepancy was the largest for UGC 00689 (3C 31) which was offset by \( \sim 120 \) mas from its expected position at the center of the map. Incorrect EOPs used in VLBA correlator job scripts from early 2003 to 2005 are likely to be responsible for this. At the time of the 5 GHz data reduction in early 2006, there was no option to correct for this effect in AIPS. For the more recently reduced 1.6 GHz data, however, we could rectify these errors by running the task CLCOR with OPCODE = “EOPS.” For the 5 GHz data, we shifted the targets to the phase center by running the task UVFIX on the SPLIT files, before attempting to create the final self-calibrated images.

Phase and amplitude self-calibration on the targets improved their images significantly at 5 GHz. All the 5 GHz images were created with uniform weighting using a ROBUST parameter = 0 in IMAGR. The Stokes \( Q \) and \( U \) maps were used in the task COMB to obtain maps of the polarization intensity and EVPA. Polarization values with \( S/N < 3 \) were blanked in COMB to produce the polarized intensity maps. The polarization angle maps were restricted in COMB to have output errors <10°. Finally, the fractional polarization maps were created in COMB by constraining the output errors to be \( \lesssim 10\% \). This latter number was relaxed to 25% for the fractional polarization image of UGC 00689. A compilation of the basic observational parameters for each source is given in Table 2. The integrated flux densities for the cores were obtained in AIPS using the Gaussian-fitting task JMFIT, while the total flux densities were obtained by putting a box around the source, using the AIPS verbs TVWINDOW and IMSTAT.

The flux density estimates for the second-epoch 1.6 GHz images were obtained from images that were convolved with circular beams of size 10 mas and had UVTAPER set to 15000 k\( \lambda \) in IMAGR. The 1.6 GHz image of the weakest source, viz., UGC 01004, was created using ROBUST = 5 in IMAGR (signifying natural weighting; the rest of the images had ROBUST = 0). This was done to get estimates in a manner similar to that done by Xu et al. (2000) for the first epoch.
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**DECLINATION (J2000)**

**RIGHT ASCENSION (J2000)**

00 39 18.5832

18.5828

18.5824

18.5820



03 19 52.540

52.538

52.536

52.534

52.532

52.530

52.528

52.526

52.524



**Figure 1.** 5 GHz VLBA total intensity image of UGC 00408. Polarization was not detected in this source. Contours are in percentage of peak surface brightness and increase in steps of 2: the lowest contour and peak surface brightness are ±0.35% and 35 mJy beam$^{-1}$, respectively.

**Table 3**

| Source Name | Phase Calibrator | $I_{\text{peak}}^{\text{cal}}$ (mJy beam$^{-1}$) | $I_{\text{int}}^{\text{cal}}$ (mJy) | $I_{\text{rms}}$ (mJy beam$^{-1}$) |
|-------------|------------------|----------------------------------|---------------------------------|-----------------------------|
| UGC 01004   | J0125−0005       | 2.3 ± 0.17                       | 2.7 ± 0.33                     | 0.22                        |
| UGC 01413   | J0155+0438       | 6.2 ± 0.08                       | 7.5 ± 0.17                     | 0.09                        |
| UGC 05073   | J0907+6815       | 20.6 ± 0.08                      | 21.9 ± 0.14                    | 0.07                        |
| UGC 06635   | J1148+1840       | ...                              | ...                            | 0.05                        |
| UGC 07115   | J1209+2547       | ...                              | ...                            | 0.12                        |
| UGC 07455   | J1217+5835       | 9.5 ± 0.09                       | 9.6 ± 0.16                     | 0.08                        |
| UGC 08419   | J1329+3154       | 3.2 ± 0.07                       | 3.8 ± 0.13                     | 0.07                        |
| UGC 12604   | J2241+4120       | ...                              | ...                            | 0.07                        |
| UGC 12531   | J2322+0812       | 14.3 ± 0.13                      | 14.7 ± 0.23                    | 0.12                        |

**Notes.** Column 1: source name. Column 2: phase-reference calibrator. Columns 3 and 4: core peak and integral intensity, respectively, as measured with JMFIT. Column 6: final rms noise in image. The images were convolved with circular beams of size 10 mas.

1.6 GHz observations. Phase self-calibration was not possible (there were too many failed solutions) for these weak targets at 1.6 GHz, except for UGC 05073 and UGC 12531. The final flux density and noise estimates at 1.6 GHz are tabulated in Table 3.

### 2.1. Results from the Radio Study

We present the 5 GHz total intensity images with the fractional polarization vectors superimposed on them, for the 10 radio galaxies with “core-jet” structures in Figures 1–11. The jets are captured in much greater detail at 5 GHz compared to 1.6 GHz (Xu et al. 2000): individual jet components and bends are more prominently highlighted. The presence of one-sided “core-jet” structures is indicative of Doppler boosting due to relativistic bulk motion in the jets on parsec scales. We note that the Doppler boosting effect results in an overestimation of the “equipartition” magnetic fields, energies, and pressures, and an underestimation of the particle lifetimes listed in Table 4. Of the 10 sources, all but three show signs of polarized emission in their parsec-scale jets. M87 was observed as the phase-reference calibrator for M84. No core polarization is detected in any of the FRI radio galaxies, except in M87. Table 5 summarizes the polarization properties.

The total intensity estimates and other properties like the jet-to-counterjet surface brightness ratio, $R_J$, are presented in Table 2. We note that the estimates for $R_J$ are typically larger than those presented in Xu et al. (2000). This is due to the different procedures adopted to derive them—while Xu et al. (2000) divided the image with a 180° rotated version of the same, and obtained average jet sidedness values from the resulting image, we have simply estimated the surface brightness along the center of the jet at a given distance from the core, and obtained the noise in the counterjet direction at approximately the same distance from the core.
Figure 4. 5 GHz VLBA total intensity image of UGC 03695 with fractional polarization electric vectors superposed. 1 mas tick = 8% polarization. Contours are in percentage of peak surface brightness and increase in steps of 2: the lowest contour and peak surface brightness are ±0.35% and 49 mJy beam$^{-1}$, respectively.

Three sources, viz., UGC 06635, UGC 07115, and UGC 12064, were not detected in the 1.6 GHz VLBA observations. These three were not observed in the first epoch observations of Xu et al. (2000). The remaining six appear to be “core-only” sources. We did not detect any jet emission in the previously “core-jet” classified source, UGC 12531. Note that “jet” emission was merely hinted at in the previous observation by Xu et al. (2000). Xu et al. had tentatively classified UGC 11718 (NGC 7052) as a “twin-jet” source at 1.6 GHz, but we see a clear “core-jet” structure at 5 GHz. It is possible that the counterjet in this source was an artifact due to errors in amplitude calibration, as was also recognized by Xu et al.

A comparison of the 1.6 GHz core peak flux densities from the two epochs of observation for the six sources is made in Figure 12. The core flux appears to have varied on average by a factor of 1.2 over a period of 5.8 years. Only the cores in UGC 01413 and UGC 05073 exhibit a slightly larger than average variation, i.e., by a factor of 1.4. This variation is
consistent with the \( \lesssim 2 \) factor variability typically observed in FRI radio galaxy cores (e.g., Sadler et al. 1994; Evans et al. 2005). The radio core prominence parameter, \( R_c \), which is a statistical indicator of beaming and thereby orientation, is = 0.02 and 0.30 in these two sources, respectively (Kharb & Shastri 2004). While UGC 05073 has a core prominence value that lies at the lower end of values exhibited by BL Lac objects (see Figure 3 in Kharb & Shastri 2004), UGC 01413 has a prominence value similar to that observed in a majority of FRI radio galaxies. While keeping in mind the fact that \( R_c \) must be cautiously used as an orientation proxy for individual sources, we do not observe a clear trend of increased core variability and orientation in the small number of galaxies considered here. Higher dynamic range images are likely required to detect jets in these sources.

2.2. Notes on Individual Sources with Polarized Emission

UGC 00689. Polarization is detected mainly along the jet edge at a distance of \( \sim 10 \) mas in UGC 00689. The polarization electric vectors are transverse to the jet direction. As the inferred magnetic field for optically thin emission is transverse to the
polarization electric vectors, this implies that the magnetic field is largely aligned ($B_\parallel$) at the jet edge. This in principle could support the scenario of jet-medium interaction which "stretches" the magnetic field lines due to "shear" at the jet edges, giving rise to an aligned magnetic field (e.g., Attridge et al. 1999). However, such field geometries can also rise from helical magnetic fields or magnetic fields with a dominant toroidal component threading these jets (e.g., Kharb et al. 2009; Clausen-Brown et al. 2011). It is interesting to note that the jet in this source has the highest fractional polarization (56% ± 17%) in the sample, approaching the theoretical maximum for optically thin incoherent synchrotron radiation. This is consistent with the magnetic field being highly ordered on parsec scales. Such a high degree of polarization (≈60%) has been observed in some blazar jets (e.g., Roberts et al. 1990; Cawthorne et al. 1993). UGC 01841. Polarization is detected largely along the jet edge at a distance of ∼10 mas in UGC 01841. The polarization electric vectors are transverse to the jet direction implying an aligned magnetic field ($B_\parallel$) at the jet edge.

Table 4

| Source Name | Length (mas) | Width (mas) | $L_{\text{rad}}$ (erg s$^{-1}$) | $B_{\text{rms}}$ (mG) | $E_{\text{min}}$ (erg) | $P_{\text{rms}}$ (dyn cm$^{-2}$) | $t_{\text{syn}}$ (yr) |
|-------------|-------------|-------------|-------------------------------|----------------------|-------------------|-------------------------------|------------------|
| UGC 11718   | 5.3         | 3.5         | 3.57E+38                      | 3.2                  | 8.00E+49          | 9.33E−07                     | 2045             |
| UGC 03695   | 6.8         | 3.5         | 9.88E+38                      | 3.1                  | 2.32E+50          | 8.76E−07                     | 2142             |
| UGC 06723   | 4.3         | 4.6         | 8.79E+39                      | 4.9                  | 1.02E+51          | 2.24E−06                     | 1059             |
| UGC 07654   | 7.5         | 6.3         | 2.20E+39                      | 7.9                  | 1.24E+50          | 5.84E−06                     | 520              |
| UGC 07494   | 4.3         | 4.6         | 9.38E+37                      | 5.1                  | 1.02E+49          | 2.45E−06                     | 998              |
| UGC 09058   | 4.3         | 3.5         | 8.18E+38                      | 3.8                  | 1.49E+50          | 1.35E−06                     | 1549             |
| UGC 01841   | 6.8         | 5.6         | 7.27E+39                      | 4.0                  | 1.14E+51          | 1.50E−06                     | 1430             |

Notes. Column 1: source name. Columns 2 and 3: length and (deconvolved) jet width used for the estimation—a small portion of the jet a few mas from the core with roughly constant brightness was chosen to get the estimates. Column 4: total radio luminosity. Column 5: "minimum" magnetic field strength. Columns 6 and 7: "minimum" energy and pressure. Column 8: synchrotron lifetime of electrons undergoing both radiative and inverse Compton (on CMB photons) losses, for a break frequency of 5 GHz.

Table 5

| Source Name | $P_{\text{peak}}$ (mJy beam$^{-1}$) | $P_{\text{rms}}$ (mJy beam$^{-1}$) | $d$ (mas) | $\chi_{\text{mean}}$ (deg) | $\Delta \chi$ (deg) | $m_{\text{mean}}$ (%) | $\Delta m$ (%) |
|-------------|----------------------------------|----------------------------------|----------|--------------------------|-------------------|---------------------|---------------|
| UGC 00408   | ...                              | 4.14E−2                          | ...      | ...                      | <5                | ...                 | ...            |
| UGC 00689   | 0.25                             | 4.75E−2                          | 10       | 52                       | 9                 | 56                  | 17             |
| UGC 01841   | 0.21                             | 4.23E−2                          | 10       | -47                      | 9                 | 25                  | 8              |
| UGC 03695   | 0.24                             | 5.01E−2                          | 4        | 81                       | 9                 | 13                  | 4              |
| UGC 06723   | 0.79                             | 4.48E−2                          | 4        | 9                        | 8                 | 5                   | 1              |
| UGC 07494   | 0.31                             | 5.03E−2                          | 3        | -83                      | 8                 | 25                  | 7              |
| UGC 07654   | 0.88                             | 8.39E−2                          | 2 core   | 42                       | 6                 | 0.13                | 0.02           |
| UGC 08433   | ...                              | 4.46E−2                          | ...      | ...                      | <4                | ...                 | ...            |
| UGC 09058   | 0.32                             | 7.66E−2                          | 3        | 46                       | 8                 | 28                  | 7              |
| UGC 11718   | ...                              | 4.29E−2                          | ...      | ...                      | <4                | ...                 | ...            |

Notes. Column 1: source name. Column 2: peak polarized intensity. Column 3: final $rms$ noise in polarization map. Column 4: distance of polarized jet component from the core. Polarization was detected from several jet components in UGC 06723 and UGC 07654. "cjet" for UGC 07654 or M87 refers to polarized emission from the "counterjet" region. Columns 5 and 6: mean polarization angle and error, respectively. Column 7: mean fractional polarization and error, respectively. Limits for jet fractional polarization for sources without a detection are listed in Column 7.
3. CHANDRA OBSERVATIONS AND DATA ANALYSIS

Of the 21 sources in the sample, eight sources have published images with the AXAF CCD Imaging Spectrometer (ACIS) on board the Chandra space telescope (Evans et al. 2006; Sambruna et al. 2003; Croston et al. 2007). The X-ray images of UGC 00597, UGC 00689, UGC 01841, UGC 06723, UGC 07360, UGC 07494, and UGC 07654 are also presented on the XJET Web site. Croston et al. (2007) describe the X-ray observations of UGC 06365. In addition, archival data exist for six other sources, viz., UGC 01004, UGC 01413, UGC 03695, UGC 08433, UGC 11718, and UGC 12064. We obtained new ~30 ks Chandra–ACIS imaging data in the VFAINT mode for UGC 00408 (see Table 6). Of the seven sources with archival or new data, UGC 01413, UGC 11718, and UGC 12064 do not show any distinctive jet-like features and moreover do not have sufficient counts in their images for a robust spectral fit. Overall, nine of the 15 UGC galaxies studied with Chandra exhibit X-ray jets in them. We focus now on the Chandra observations of UGC 00408 and UGC 08433.

Starting with level 1 event files, we removed the position randomization and applied the appropriate corrections for gain and charge transfer efficiency. Level 2 event files were obtained by following appropriate steps described in the Chandra data reduction threads. We used the “Subpixel Event Repositioning” technique described by Li et al. (2003, 2004), to improve the image resolution. Spectra were extracted from different regions for each of the sources. The data were binned so that each bin had at least 20 counts. The spectra of the core and jet structures were extracted and analyzed separately. The core spectrum was extracted from a circular region of radius 1″ centered on the brightest pixel. An aperture of this size includes 90% of the total flux at 1 keV from a point source from that region. Jet spectra were extracted from rectangular regions adjusted to minimize non-jet emission. However, there were insufficient counts for an independent fit for the jet spectra for either source.

3.1. Results from the X-Ray Study

UGC 00408 (NGC 193). This S0 galaxy is part of a galaxy group and seems to have a companion, NGC 204. The Chandra–ACIS observations reveal X-ray emission along the radio jet (Figure 13), extending approximately 5" (~1.5 kpc). The nuclear spectrum can be adequately described by a simple power law, with absorption consistent with the Galactic column. The number of counts was too low to justify more complex modeling. The distribution of the large-scale diffuse emission can be seen more clearly in Figure 14. By smoothing the Chandra image with a Gaussian of kernel radius 20 in DS9, we could clearly discern the presence of a bubble-like structure centered around the AGN, with a maximum outer radius of 107" (~29 kpc). We extracted counts from this region, after excluding the inner region of about 19" where the AGN emission dominates, using the CIAO software version 4.3 (CALDB version 4.4.6). We fitted a thermal gas model to the diffuse emission using the XSPEC

Table 6

| Source      | OBSID | Observer | Date       | Exposure | Instrument |
|-------------|-------|----------|------------|----------|------------|
| UGC 00408   | 4053  | O’Dea    | 2003 Sep 1 | 29.44 ks | ACIS       |
| UGC 08433   | 4055  | Sambruna | 2003 Nov 25| 30.97 ks | ACIS       |

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10 See the online proceedings of the NRAO-NAASC 2012 Workshop titled “Outflows, Winds, and Jets: From Young Stars to Supermassive Black Holes.”

11 http://hea-www.harvard.edu/XJET/
software (model = wabs*MEKAL). The neutral hydrogen column density was frozen to the Galactic value in the direction of NGC 193 (=2.79E+22 cm$^{-2}$). The modeling yielded a best-fit temperature of 0.80 ± 0.01 keV for the X-ray gas and a reduced $\chi^2$ value of 1.12 for 237 degrees of freedom. The unabsorbed 0.5–7 keV X-ray flux from the entire bubble-like structure is $\sim 4.4E-13$ erg cm$^{-2}$ s$^{-1}$. We estimated the work ($W$) done on the gas by the inflation of the bubble using the simple relation, $W = nkTV$, where $n$ was the hydrogen density, assumed to be 0.1 cm$^{-3}$ (e.g., Mathews & Brighenti 2003), and $V$ was the volume of the entire bubble (not just the X-ray cavity; see below), assumed to be spherical and uniformly filled with the 0.8 keV
X-ray gas. This work turns out to be possible with a Gaussian of width ∼2 pixels.

Figure 14. Color image highlights large-scale diffuse emission detected approximately 1′ from the nucleus in UGC 00408. The X-ray image has been smoothed with a Gaussian of width = 2 pixels.

(A color version of this figure is available in the online journal.)

X-ray gas. This work turns out to be possible with a Gaussian of width = 2 pixels. X-ray gas. This work turns out to be possible with a Gaussian of width = 2 pixels. X-ray gas. This work turns out to be possible with a Gaussian of width = 2 pixels.

Table 7
X-Ray Spectral Analysis: UGC 00408 and UGC 08433

| Source Name | XSPEC Model | Best-fit Parameters | Flux 1 keV (erg cm⁻² s⁻¹ keV⁻¹) | Luminosity 1 keV (erg s⁻¹ keV⁻¹) |
|-------------|-------------|---------------------|---------------------------------|----------------------------------|
| UGC 00408   | phabs*power law | $N_H = 8.46^{+0.11}_{-0.08} \times 10^{20}$ cm⁻², $\alpha = 0.68^{+0.05}_{-0.02}$, $\chi^2$/dof = 9.43/6 | $1.8 \times 10^{-14}$ | $7.8 \times 10^{39}$ |
| UGC 08433   | phabs*power law | $N_H = 8.69^{+0.29}_{-0.28} \times 10^{23}$ cm⁻², $\alpha = 0.62^{+0.04}_{-0.00}$, $\chi^2$/dof = 9.43/6 | $2.9 \times 10^{-14}$ | $1.3 \times 10^{40}$ |

Notes. Column 3: $N_H$ = the hydrogen column density. Columns 4 and 5: aperture corrected flux density and luminosity density, respectively, at 1 keV.

4.1. Polarization Detection: Depolarizing Medium

Polarization traces the orderliness and orientation of the magnetic field in a source. If the magnetic field is tangled, the polarization may change on scales too small to be resolved by the telescope, giving rise to “beam” depolarization (e.g., Laing 1980). Another factor affecting the observed degree of polarization could be large amounts of ionized gas in the central region. Extended X-ray emission is detected in a large number of FRI sources observed with the Chandra X-ray Observatory (e.g., Mathews & Brighenti 2003). Ionized gas containing a magnetic field would cause Faraday rotation of the polarized light: if the regions with different EVPAs are not resolved by the telescope, “beam” depolarization would occur. If the Faraday rotating medium is mixed with the synchrotron emitting electrons, then Faraday rotation occurring at various depths of the source would result in “internal” depolarization (Burn 1966; Cioffi & Jones 1980). We briefly explore candidates for the Faraday rotating medium for the core and jet components below.

4.1.1. Core Polarization

Polarization is not detected in the cores of 9 of the 10 FRI sources. Only the core region of M87 exhibits polarized emission, consistent with the preliminary results of C. Walker et al. (2012, in preparation). The lack of polarization in almost all the sources could be signifying the presence of ionized gas on parsec scales in these sources. The inner ionized edge of the tori could be a suitable candidate for the Faraday rotating medium. The broad-line clouds, or the intercloud medium (e.g., O’Dea 1989) could be other candidates. However, if it is supposed that FRIs lack obscuring tori and a significant broad-line region, as proposed on the basis of the high detection rate of optical nuclei in HST images (e.g., Chiaberge et al. 1999; Kharb & Shastri 2004), then this lack of polarization could either suggest disordered magnetic fields (however, see...
the discussion on sensitivity below), the presence of diffuse ionized gas in the nuclear regions and/or beam depolarization. The fact that core polarization is detected only in the nearest, most well-resolved source, M87, is consistent with the latter suggestion.

For the sample source UGC 07360 (3C 270), Kharb et al. (2005) detected a core fractional polarization of 0.4%. Since Kharb et al. had used a global VLBI array including the 100 m Effelsberg antenna, it is possible that the lower sensitivity of the current data plays a role in the non-detections. We note that the
typical core fractional polarization observed in radio galaxies is \(\lesssim 1\%\) (Rudnick et al. 1986; Kharb et al. 2003, 2005; Kharb 2004). Gliozzi et al. (2003) found that the Chandra and XMM data of 3C 270 were best fit by a Compton thick absorber \((N_H \sim 5 \times 10^{22}\text{ cm}^{-2})\) with a covering factor of \(\sim 80\%\). Therefore, beam depolarization and inadequate sensitivity could be important factors in the lack of core polarization in these galaxies.

4.1.2. Jet Polarization

We detect polarization in some parts of the parsec-scale jets of 7 out of 10 FRI radio galaxies. The fractional polarization in the jets is typically between 5% and 25% (Table 3). The jet segment in UGC 00689 has the highest fractional polarization \((56\% \pm 17\%)\) in the sample, close to the theoretical maximum for optically thin incoherent synchrotron radiation, and consistent with a highly ordered magnetic field on parsec scales. The inferred magnetic field is mostly aligned with the jet direction in four of the seven sources, viz., UGC 00689, UGC 01841, UGC 07499, and UGC 07654 (M87). It appears to be oblique to the jet direction along the spine of UGC 06723 (3C 264), but more aligned at the edges. Such a “spine-sheath” structure can either be explained as shocks along the jet spine and shear along the edges due to jet-medium interaction, or simply by the presence of a helical magnetic field (Lyutikov et al. 2005; Kharb et al. 2008a, 2008b).

Oblique polarization electric vectors are also observed in UGC 03695 and UGC 09058. These could arise due to Faraday rotation by an ionized screen. At 5 GHz, an RM of \(\sim 218\text{ rad m}^{-2}\) would be required to rotate the EVPAs by 45°. We note that when RM is actually measured in FRI radio galaxy jets through multi-frequency polarimetric observations, it turns out to be the order of a few 100 rad m\(^{-2}\) (e.g., Taylor et al. 2001; Zavala & Taylor 2002; Kharb et al. 2009). Kharb et al. (2009) reasoned that such an RM could result from a thin sheath (with a path length of say, \(\sim 10\%) of the jet width) surrounding the main synchrotron emitting body of the jet. While narrow-line clouds on parsec scales could also give rise to these RM, the short time-scale RM variability (over a few months) observed in a few sources, questions the suitability of narrow-line region as a candidate (Asada et al. 2008). Hot X-ray emitting gas observed with Chandra is a possible candidate for the Faraday rotating medium. However, the large path lengths involved for the polarized light, could result in large values for RM (several 1000 rad m\(^{-2}\)), which would then necessitate many reversals in the magnetic field direction to give final RM values of a few 100 rad m\(^{-2}\). This would result in net depolarization at lower radio frequencies, an effect that is not observed in radio galaxy studies with multi-frequency observations (e.g., Kharb et al. 2009). But since this effect cannot yet be confirmed or rejected in the sample sources, the hot diffuse gas cannot be ruled out as a candidate for Faraday rotation.

We detect significant fractional polarization in the jet of UGC 06723 or 3C 264. The degree of polarization is about \(22\% \pm 7\%) in the jet knot \(\sim 15\) mas from the core and has an average value of \(13\% \pm 2.5\%) over the entire length of the jet. However, the jet also appears one-sided on kiloparsec scales (Baum et al. 1997a) suggesting a small inclination angle. Thus, the high polarization observed may be due to favorable orientation which Doppler boosts the radio emission. This can happen if individual jet components move with different Lorentz factors, so that the component with the faster speed dominates the polarized emission at smaller angles to line of sight (e.g., Narayan & Piran 2012).

As we discuss below, the 5 GHz observations are unable to resolve the jet structure in the transverse direction. Therefore, we conclude that beam depolarization is the major cause of the lack of polarization in the parsec-scale jets of these FRI radio galaxies. This is consistent with the finding that in the observations of 3C 264 by Kharb et al. (2009), the average fractional polarization for a jet knot \(\lesssim 2\) mas from the core, which displayed an EVPAs of \(\sim 45\)° with respect to the jet direction (see also Figure 5), decreased from 2.5% \(\pm 0.5\%\) at 5 GHz to 5% \(\pm 0.7\%) at 8 GHz. As RM gradients resulting from helical magnetic fields, or Faraday rotation from hot ionized gas, could both be occurring in these parsec-scale jets, adequate resolution (e.g., at 15 GHz) will be crucial for the detection of jet polarization.

4.2. Jet Surface Brightness “Dimming”

Assuming that the VLBI jet is expanding adiabatically, and the number of relativistic particles and magnetic flux is conserved, then a simple relation exists between the jet surface brightness \(I_\nu\), jet radius \(r\), and jet velocity \(v\) (Baum et al. 1997b):

\[
I_\nu \propto (\Gamma v)^{-(\gamma+2)/3} \frac{r^{-(5\gamma+4)/3} D^{2+\alpha}}{D_{\theta}^{2\alpha}}
\]

for a predominantly longitudinal magnetic field, and

\[
I_\nu \propto (\Gamma v)^{-(5\gamma+7)/6} \frac{r^{-(7\gamma+5)/6} D^{2+\alpha}}{D_{\theta}^{2\alpha} f(D, \theta)}
\]

for a predominantly transverse magnetic field, where \(\alpha\) is the jet spectral index, \(\gamma = 2\alpha + 1\), \(\Gamma\) is the Lorentz factor \((\equiv 1 - (1 - \beta^2)^{-1/2})\), \(D\) is the Doppler factor \((\equiv \Gamma (1 - \beta \cos \theta)^{-1})\), \(\beta \equiv v/c\), and \(\theta\) is the jet orientation angle with respect to the line of sight.

Two major assumptions have been made here. The first is that there is no velocity gradient transverse to the jet, and the second is that the emission is isotropic in the jet rest frame. Taking into account the anisotropy in emission, which is important given the nature of synchrotron emission, the relations (1) and (2) above are modified to the following:

\[
I_\nu \propto (\Gamma v)^{-(\gamma+2)/3} \frac{r^{-(5\gamma+4)/3} D^{3+2\alpha}}{D_{\theta}^{2\alpha}}
\]

for a predominantly longitudinal magnetic field, and

\[
I_\nu \propto (\Gamma v)^{-(5\gamma+7)/6} \frac{r^{-(7\gamma+5)/6} D^{2+\alpha} f(D, \theta)}{D_{\theta}^{2\alpha} f(D, \theta)}
\]

for a predominantly transverse magnetic field (Beigelman 1993; Bondi et al. 2000). The function “\(f(D, \theta)\)” in Equation (4) depends on the precise form of the field structure and must be computed numerically (e.g., Laing 2002) for a given source. However, the anisotropy effect is much less extreme for fields without a longitudinal component and/or fields that are not highly ordered. A toroidal field, for example, would give a similar variation as the two-dimensional field sheet case, which is much less extreme (R. Laing 2012, private communication).

Using therefore Equations (3) and (2) for poloidal and toroidal magnetic-field dominated regions, respectively, we have for \(\alpha = 0.7\),

\[
I_\nu \propto (\Gamma v)^{-1.46} r^{-5.33} D^{4.4}
\]

(5)

\[
I_\nu \propto (\Gamma v)^{-3.16} r^{-3.63} D^{2.7}
\]

(6)

In order to look for jet expansion on parsec scales, we examined the deconvolved jet width \(\sigma\), which is \(\sqrt{\sigma_\text{obs}^2 - \sigma_\text{beam}^2}\), \(\sigma_{\text{obs}}\), and \(\sigma_{\text{beam}}\) being the FWHM of the observed jet...
width and telescope beam, respectively. For this analysis, we used images which were restored with circular beam sizes of $2.5 \times 2.5$ mas and were rotated so that the core-jet structure lay along the east–west axis (specifically at a P.A. of $-90^\circ$). We found that the deconvolved jet width was typically of the order of 1 mas, which was less than half the beam size, basically suggesting that the jets were unresolved on these scales. More sensitive, higher frequency (e.g., 15 GHz) VLBA observations are therefore required to look for jet expansion on these scales.

The peak surface brightness $I_\nu$ in the jets falls with distance $d$ from the core following a power-law relation, $I_\nu \propto d^{-a}$ (e.g., Walker et al. 1987). We examined this relation in 10 sources with jets clearly resolved along their lengths (see Figures 16–18). All images were first restored with circular beam sizes of $2.5 \times 2.5$ mas and rotated as discussed above. Gaussians were fit to slices transverse to the jet direction using the IDL routine GAUSSFIT. The input errors on the surface brightness values were taken to be the rms noise in the radio images (we assumed a conservative noise estimate of 0.1 mJy beam$^{-1}$ for all sources). We found that for distances $\lesssim 5$ mas, the peak surface brightness exhibited a steep slope with $a$ typically around $-3$ (Table 8). (We note that while the slopes were derived from oversampled data, only the significant points spaced at about half the beam size (i.e., at every 1.0–1.5 mas), have been plotted in Figures 16–18). This inner region is likely to be affected by the presence of the bright unresolved core and jet. A slope of $-3$ in the log($I_\nu$) versus log($d$) plot implies a Gaussian with a standard deviation of $\sim 2.3$ mas, centered on the radio core peak position.

![Figure 16. Jet peak surface brightness with respect to the distance from the core. cf. Table 8 and Section 4.2 for a description of the two slopes.](image)

| Source Name | Slope1 | Slope2 | Break (mas) |
|-------------|--------|--------|-------------|
| UGC 00408   | $-3.28 \pm 0.09$ | $-3.59 \pm 0.15$ | 3.5 |
| UGC 00689   | $-3.03 \pm 0.04$ | $-1.43 \pm 0.22$ | 4.0 |
| UGC 01841   | $-1.85 \pm 0.04$ | $-1.20 \pm 0.08$ | 5.0 |
| UGC 03695   | $-2.94 \pm 0.15$ | $-1.44 \pm 0.10$ | 5.0 |
| UGC 06723   | $-1.36 \pm 0.06$ | $-2.09 \pm 0.06$ | 5.5 |
| UGC 07494   | $-3.33 \pm 0.08$ | $-1.92 \pm 0.15$ | 5.0 |
| UGC 07654   | $-2.14 \pm 0.05$ | $-1.08 \pm 0.05$ | 5.0 |
| UGC 08433   | $-2.84 \pm 0.04$ | $-3.60 \pm 0.20$ | 4.0 |
| UGC 09058   | $-3.51 \pm 0.17$ | $-3.50 \pm 0.30$ | 4.0 |
| UGC 11718   | $-3.47 \pm 0.12$ | $-4.04 \pm 0.33$ | 3.5 |

Notes. Slope1 is derived for distances $\lesssim 5$ mas from the radio core, while Slope2 is derived for distances $> 5$ mas and until the jet surface brightness falls below three times the rms noise level. Column 3: the number of data points used in the estimation of Slope1. Column 5: the distance from the core where the slope transitions from 1 to 2.

For distances between 5 and 20 mas from the radio cores, the slope $a$ varies typically between $-1$ and $-2$ (Table 8). The average $a$ value for all 10 jets turns out to be $-2.1$. However, three jets, viz., UGC 08433 (NGC 5141), UGC 09058 (NGC 5490), and UGC 11718 (NGC 7052), have much steeper slopes of around $-3.5$. This makes them shorter compared to other jets. Excluding these three jets results in an average $a$ value of about $-1.5$. It is interesting to note that UGC 06723
Figure 17. Jet peak surface brightness with respect to the distance from the core. cf. Table 8 and Section 4.2 for a description of the two slopes.

Figure 18. Jet peak surface brightness with respect to the distance from the core. cf. Table 8 and Section 4.2 for a description of the two slopes.

(3C 264), UGC 08433, UGC 09058, and UGC 11718 have steeper slopes for distances greater than 5 mas than for distances less than 5 mas, unlike the rest of the sources. The surface brightness slope for the jet in UGC 09058 remains almost constant for all distances. Of these, 3C 264 is a well-known head–tail source in a galaxy cluster and appears to be strongly interacting with the medium. NGC 7052 on the other hand, seems to reside in a relatively isolated environment. Therefore, it is difficult to identify any obvious reason for the steep slopes in these sources, without having more information on their jet orientations.

Radiative losses through synchrotron and inverse Compton (IC)/cosmic microwave background (CMB) emission are not significant on parsec scales as the typical electron lifetimes are of the order of a 1000 years (see Table 4). However, IC losses from seed photons in the relativistic portion of the jets (e.g., the jet “spine”) could still play a role in the surface brightness “dimming.” Such a scenario, wherein the slower moving jet “sheath” sees the beamed radiation produced by the jet “spine,” and undergoes IC losses, has been put forth for gamma-ray emitting AGNs (Ghisellini et al. 2005). Also, external photons from the accretion disk could cause IC losses in the jet electrons.
Assuming for now that adiabatic expansion losses are primarily responsible for the jet intensity “dimming,” two limiting cases could be considered: (1) constant jet velocity and (2) constant jet radius.

1. If the jet is moving at a constant velocity on parsec scales, then in order to obtain a $\log(I_\nu) - \log(d)$ slope of $-1.5$, the radius of the jet $r$ should be related to distance along the jet $d$ as $r \propto d^p$, with exponent $p = 0.28$ and 0.41 for the poloidal and toroidal magnetic fields, respectively. This implies a small jet expansion rate, which is unobservable in the 5 GHz observations. Thus, higher frequency observations, which can resolve the jet in the transverse direction, are needed to observe this expansion. For the three sources with slopes $\sim -3.5$, $p$ would have to be 0.66 and 0.96 for the poloidal and toroidal magnetic field case, respectively.

Walker et al. (1987) have found that the jet in the radio galaxy 3C 120 has a $\log(I_\nu) - \log(d)$ slope of $\approx -1.3$ over parsec as well as on kiloparsec scales. A much flatter slope of $\sim -0.75$ is observed in the MERLIN$^{12}$ jet (100 parsec scale) of 3C 264 (see Baum et al. 1997b). The exponent $p$ would therefore need to be 0.24 and 0.36 for 3C 120, and 0.14 and 0.21 for 3C 264, for poloidal and toroidal magnetic fields, respectively. Interestingly, whenever the jets are laterally resolved in 3C 120, a $p$ value of 0.25–0.35 is actually observed (see Figure 16 of Walker et al. 1987). This is also true for the 100 parsec-scale jet of 3C 264, where a $p$ value of 0.22 is observed for jet distances between 100 and 300 pc, and a $p$ of 0.16 for jet distances between 400 and 600 pc (see Figure 10 of Baum et al. 1997b).

Giroletti et al. (2004) have reported that the jet in the BL Lac object, Mrk 501, which could be considered a beamed counterpart of an FRI radio galaxy in the Unified Scheme, exhibits a $\log(I_\nu) - \log(d)$ slope of $-1.5$ for distances $< 35$ mas (≈23 pc) from the core, and $-0.4$ for distances between 40 and 110 mas (≈26–73 pc). However, unlike the case of 3C 120, where the slope remains constant from parsec to kiloparsec scales, the slope in Mrk 501 varies from $-1.2$, $-1.9$, $+0.6$ to $-0.9$, as the distance from the core increases from 100 to 500 mas (≈66–331 pc; see Figure 5 of Giroletti et al. 2008). For Mrk 501, the (log of the) jet radius with respect to the (log of the) core distance has a slope of 0.5 for distances $< 35$ mas from the core, and 0.3 for distances between 40 and 110 mas. Therefore, in sources where the jets can be resolved in the transverse direction, a slow jet expansion is indeed observed, as predicted by scenario (1). This makes scenario (1) a viable option for explaining the jet intensity behavior.

2. If the jet has a constant radius on parsec scales (a cylindrical jet), then a $\log(I_\nu) - \log(d)$ slope of $-1.5$ requires that the jet speed $v$ vary with distance $d$ as $v \propto d^q$ (an accelerating jet!), with exponent $q = 0.22, 0.15, 0.10$, and 0.04, for initial jet velocities $75$ pc; see Figures 16–18), irrespective of the dominant magnetic field structure. Accelerating parsec-scale jets have significant implications: they are consistent with the phenomenon of “magnetic driving” in Poynting-flux-dominated jets (Komissarov 1999; Vlahakis & Königl 2004). It is worth noting that several VLBI monitoring studies have detected

“accelerating” jet knots (e.g., Hough et al. 1996; Cotton et al. 1999; Sudou et al. 2000), consistent with scenario (2).

The $q$ estimates derived above are in essence upper limits, as increasing them makes $\beta > 1$, for the above assumed maximum distance and initial jet speeds. Correspondingly, lower limits to the jet inclination angles with respect to the line of sight, $\theta$, can be derived. For sources with $\log(I_\nu) - \log(d)$ slopes of $-1.5$, lower limits on $\theta$ must lie between 15° and 25° for the above jet speeds for a toroidal magnetic-field-dominated region; and between 30° and 50° for a poloidal magnetic field region. For the three sources with slopes $\sim -3.5$, lower limits on $\theta$ would need to be around 80°–90° for the toroidal magnetic field region, but > 90° for the poloidal magnetic field regions, which is physically implausible. Therefore, the above scenario can explain the entire range of observed slopes best for the case of toroidal magnetic fields. In addition, the sources with steep slopes must lie close to the plane of the sky, consistent with the Doppler dimming effect causing a sharper drop in their jet brightness.

However, there are several cons to this model: if the jet continued to accelerate, its speed would exceed the speed of light beyond the range of distances considered here (e.g., for $d \geq 5$ pc). This is unphysical and would require that the jets only accelerate over the range of scales seen here, i.e., $\sim 0.5$ to $\sim 3.5$ pc. While a different range of $q$ parameters could produce the observed slopes for larger distances (say, 100 parsec scale), the $q$ values become progressively small, indicating a weaker dependence between the jet speed and distance. In addition, the above $q$ values depend strongly on the jet starting distance, and the total distance considered, making this case not so well constrained. It is worth noting that VLBI monitoring also reveals jet knots that are either stationary, decelerating, or moving at constant speeds (e.g., Jorstad et al. 2005; Homan et al. 2009). Finally, the assumption that the jet radius remains the same on kiloparsec scales as on parsec scales in FRI radio galaxies, is unrealistic.

Recent relativistic numerical MHD simulations have provided invaluable insights into the collimation and acceleration of AGN jets. These simulations show that when the jet becomes unconfined and conical, the magnetic pressure gradient which accelerates the jet, is balanced by the tension of the toroidal magnetic field which slows down the jet. Therefore, jet acceleration saturates when the jet becomes conical (Tchekhovskoy et al. 2008, 2009; Lyubarsky 2009). Probing the jet in M87 from the sub-parsec to 100 parsec scale, Asada & Nakamura (2012) have found that the jet streamlines appear to change from parabolic to conical at a deprojected jet distance of about 250 pc. Therefore, if the FRI jets become unconfined and conical on scales of a few tens of to a few hundred parsecs, then jet acceleration as outlined in scenario (2) above, cannot be ruled out in the present data. Higher resolution polarization-sensitive radio observations which can laterally resolve the jets and indicate the magnetic field structure, as well as observations that probe jet emission from parsec to kiloparsec scales, are required to gain further insight into the jet evolution in FRIs.

4.3. The Ubiquity of X-Ray Jets in FRIs

Fifteen of the sample of 21 UGC radio galaxies have been observed with Chandra (see Tilak 2007 and references therein). Of these, X-ray jets are detected in nine sources (viz., NGC 193,
NGC 315, 3C 31, 3C 66B, 3C 264, 3C 270, M84, M87, and NGC 5141). The high frequency of occurrence of X-ray jets in this complete sample suggests that they are a signature of a ubiquitous and important process in FRI jets. The X-ray jets in FRI radio galaxies are thought to be synchrotron emission (e.g., Sambruna et al. 2004; Worrall 2009). The short life times jets in FRI radio galaxies are thought to be synchrotron emission a ubiquitous and important process in FRI jets. The X-ray in this complete sample suggests that they are a signature of NGC 5141). The high frequency of occurrence of X-ray jets are consistent with the phenomenon of “magnetic driving” in Poynting-flux-dominated jets. The main caveat to case (2) is that if the jet continued to accelerate beyond the narrow range of distances considered here, its speed would become larger than the speed of light, which is clearly unphysical. However, if the jets become conical on 100 parsec scales, as suggested in M87 (Asada & Nakamura 2012), then case (2) may still be viable. While slow jet expansion is indeed indicated in a few sources that have been resolved in the transverse direction, such as Mrk 501, 3C 264, and 3C 120, on scales of tens to hundreds of parsecs, in agreement with the predictions of case (1), case (2) cannot be ruled out in the present data. Radio observations that probe jet emission all the way from parsec to kiloparsec scales are required to fully understand the jet evolution in FRI radio galaxies.

5. The X-ray image of UGC 00408 (NGC 193) shows the presence of an X-ray bubble with a cavity radius of ~16 kpc. We estimate that the work done on the X-ray gas by the inflation of the bubble is ~7×10^48 erg.

6. Of the 15 sample UGC radio galaxies observed with Chandra, X-ray jets are detected in nine sources. The high frequency of occurrence of X-ray jets suggests that they are a signature of a ubiquitous and important process in FRI jets. It appears that the FRI jets start out relativistically on parsec scales but decelerate on kiloparsec scales, and the X-ray emission reveals the location of particle reacceleration due to bulk deceleration in their jets.

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5. SUMMARY AND CONCLUSIONS

We have presented here the results from a VLBA observational study of 19 UGC FRI radio galaxies at 1.6 and 5 GHz. Polarization-sensitive VLBA observations were carried out for 10 “core-jet” sources at 5 GHz, while second-epoch 1.6 GHz observations were carried out for nine “core-only” sources. Chandra–ACIS images and spectral fits for two UGC sources with X-ray jets are also presented in the paper. We examine the jet surface brightness “dimming” on parsec scales and derive constraints on jet evolution. The main results are summarized below.

1. The one-sided “core-jet” morphology in 10 sources at 5 GHz is consistent with relativistic jet velocities on parsec scales in these FRI radio galaxies. The second-epoch 1.6 GHz observations failed to detect any new jets in the nine “core-only” sources. Even more sensitive observations (with rms noise lower than 5 × 10^{-5} Jy beam^{-1}) are therefore required to detect parsec-scale jets in them.

2. Seven of the ten sources studied show some polarization in their parsec-scale jets at 5 GHz. UGC 06723 (3C 264) shows the most extensive polarization in its jet, with the polarization electric vectors suggesting a complex magnetic field structure reminiscent of a “spine-sheath” structure. Polarization seems to be detected close to the jet edge in a couple of sources with an aligned magnetic field (B_{||}) geometry, which could either be suggestive of “shearing” due to jet-medium interaction or a helical magnetic field. In a few cases the polarization electric vectors are oblique with respect to the jet direction. This could indicate a Faraday screen of ionized gas that may have rotated the polarization electric vectors, or the presence of oblique shocks. A thin outer layer of the jet could in principle serve as the Faraday screen.

3. The peak intensity (I_v) in the parsec-scale jets falls with distance (d) from the core following a power-law relation, I_v \propto d^{p}, with p varying between -1 and -2 (typical p \approx -1.5). Three sources with short jets have steeper slopes of about -3.5.

4. On the assumption that adiabatic expansion losses are primarily responsible for the jet surface brightness “dimming,” two limiting cases are considered: (1) the jet has a constant speed on parsec scales and is expanding gradually, but the expansion is not visible in the 5 GHz images, or (2) the jet has a constant radius and is accelerating on parsec scales. In order to explain the whole range of observed log(I_v) versus log(d) slopes, the jet must be dominated by toroidal magnetic fields, in the latter case. Accelerating parsec-scale jets are consistent with the phenomenon of “magnetic driving” in Poynting-flux-dominated jets. The main caveat to case (2) is that if the jet continued to accelerate beyond the narrow range of distances considered here, its speed would become larger than the speed of light, which is clearly unphysical. However, if the jets become conical on 100 parsec scales, as suggested in M87 (Asada & Nakamura 2012), then case (2) may still be viable. While slow jet expansion is indeed indicated in a few sources that have been resolved in the transverse direction, such as Mrk 501, 3C 264, and 3C 120, on scales of tens to hundreds of parsecs, in agreement with the predictions of case (1), case (2) cannot be ruled out in the present data. Radio observations that probe jet emission all the way from parsec to kiloparsec scales are required to fully understand the jet evolution in FRI radio galaxies.

5. The X-ray image of UGC 00408 (NGC 193) shows the presence of an X-ray bubble with a cavity radius of ~16 kpc. We estimate that the work done on the X-ray gas by the inflation of the bubble is ~7×10^48 erg.

6. Of the 15 sample UGC radio galaxies observed with Chandra, X-ray jets are detected in nine sources. The high frequency of occurrence of X-ray jets suggests that they are a signature of a ubiquitous and important process in FRI jets. It appears that the FRI jets start out relativistically on parsec scales but decelerate on kiloparsec scales, and the X-ray emission reveals the location of particle reacceleration due to bulk deceleration in their jets.

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