FARADAY ROTATION STRUCTURE ON KILOPARSEC SCALES IN THE RADIO LOBES OF CENTAURUS A

I. J. Feain1, R. D. Ekers1, T. Murphy2,3, B. M. Gaensler2, J-P Macquart4, R. P. Norris1, T. J. Cornwell1, M. Johnston-Hollitt5, J. Ott6, and E. Middelberg7

1 CSIRO Australia Telescope National Facility, P.O. Box 76, Epping, NSW 1710, Australia; ilana.feain@csiro.au
2 Sydney Institute for Astronomy, School of Physics, The University of Sydney, NSW 2006, Australia
3 School of Information Technologies, The University of Sydney, NSW 2006, Australia
4 Curtin Institute of Radio Astronomy, Curtin University of Technology, GPO Box U1987, WA 6845, Australia
5 School of Chemical and Physical Sciences, Victoria University of Wellington, PO Box 600, Wellington, New Zealand
6 National Radio Astronomical Observatory, P.O. Box 1003 Lopezville Road, Socorro, NM 87801-0387, USA
7 Astronomisches Institut der Universität Bochum, Universitätsstr. 150, 44801 Bochum, Germany

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ABSTRACT

We present the results of an Australia Telescope Compact Array 1.4 GHz spectropolarimetric aperture synthesis survey of 34 deg² centered on Centaurus A–NGC 5128. A catalog of 1005 extragalactic compact radio sources in the field to a continuum flux density of 3 mJy beam⁻¹ is provided along with a table of Faraday rotation measures (RMs) and linear polarized intensities for the 28% of sources with high signal to noise in linear polarization. We use the ensemble of 281 background polarized sources as line-of-sight probes of the structure of the giant radio lobes of Centaurus A. This is the first time such a method has been applied to radio galaxy lobes and we explain how it differs from the conventional methods that are often complicated by depth and beam depolarization effects.

Assuming a magnetic field strength in the lobes of 1.3 B₁ μG, where B₁ = 1 is implied by equipartition between magnetic fields and relativistic particles, the upper limit we derive on the maximum possible difference between the average RM of 121 sources behind Centaurus A and the average RM of the 160 sources along sightlines outside Centaurus A implies an upper limit on the volume-averaged thermal plasma density in the giant radio lobes of $n_e < 5 \times 10^{-3} B_1^{-1}$ cm⁻³. We use an RM structure function analysis and report the detection of a turbulent RM signal, with rms $\sigma_{\text{RM}} = 17$ rad m⁻² and scale size 0:3, associated with the southern giant lobe. We cannot verify whether this signal arises from turbulent structure throughout the lobe or only in a thin skin (or sheath) around the edge, although we favor the latter. The RM signal is modeled as possibly arising from a thin skin with a thermal plasma density equivalent to the Centaurus intragroup medium density and a coherent magnetic field that reverses its sign on a spatial scale of 20 kpc. For a thermal density of $n_1 = 10^{-3}$ cm⁻³, the skin magnetic field strength is 0.8 $n_1^{-1}$ μG.

Key words: galaxies: individual (Centaurus A, NGC 5128) – techniques: interferometric – techniques: polarimetric

Online-only material: color figures, machine-readable tables

1. INTRODUCTION

The lobes of radio galaxies are magnetized, quasi-freeely expanding rarified cavities inflated by relativistic jets propagating outward through the intergalactic medium from a central supermassive black hole (e.g., Begelman et al. 1984). As such, radio lobes could be excellent sites for high-energy particle acceleration and even the production of ultra-high-energy cosmic rays (Benford & Protheroe 2008; Fraschetti & Melia 2008; Hardcastle et al. 2009). Knowledge of the physical conditions in radio lobes, including both the lobe magnetic field strength and thermal plasma density, are important to explore any high-energy acceleration mechanisms in full (Kronberg et al. 2004).

Understanding the magnetic and thermal properties of radio lobes in detail is also fundamental to our understanding of galaxy formation in terms of feedback processes between the active galactic nucleus (AGN) and the interstellar/intergalactic medium (Croton et al. 2006; Croft et al. 2006; Elbaz et al. 2009).

Linearly polarized electromagnetic radiation passing through a magnetized thermal plasma causes rotation in the angle of polarization of the radiation at a rate given by

$$\delta \theta = 0.81 n_e B_\parallel \delta \Omega \lambda^2$$

$$= \delta \text{RM} \lambda^2,$$  \hspace{1cm} (1)

where $\theta$ (in radians) is the position angle of the radiation at wavelength $\lambda$ (in meters), $n_e$ is the thermal electron density (in cm⁻³), $B_\parallel$ is the line of sight component of the magnetic field (in μG), $l$ is the path length through the rotating material (in pc), and rotation measure (RM) is the Faraday RM (in units of rad m⁻²).

If radio galaxy lobes contain magnetized, thermal plasma, they will have an associated intrinsic Faraday depth. Observations of RMs in radio sources have shown that internal Faraday rotation in radio lobes is quite small (Kronberg et al. 1986, 2004; Schoenmakers et al. 1998; Palma et al. 2000) with estimates of the thermal electron densities of $n_e \lesssim 10^{-6} \text{ cm}^{-3}$, assuming that a thermal plasma is distributed uniformly across the lobes. Such low inferred thermal matter densities are orders of magnitude lower than the upper limits on hot (keV) gas obtained from measurements of X-ray cavities around radio lobes (Blanton et al. 2001; Fabian et al. 2000; Nulsen et al. 2005).

Whereas only upper limits exist on the uniform thermal matter density inside radio lobes, there is conflicting evidence regarding the presence of a Faraday rotating thin skin (or sheath) around the lobes caused by entrainment of intergalactic plasma. For example, in the case of Cygnus A, Dreher et al. (1987) attribute observed RM variations of thousands of rad m⁻² wholly to the foreground intracluster medium that Cygnus A is embedded...
within. Bicknell et al. (1990), however, use the same data to show that this RM structure could arise from a thin skin around the radio lobes where Kevin–Helmholtz instabilities have caused a mixing of the lobe plasma with the intergalactic medium. More recently, a similar debate has arisen as to the origin (intracluster medium versus thin skin) of RMs (and RM variations) in excess of \( \pm1000 \text{ rad m}^{-2} \) across the radio galaxy PKS 1246–410 in the center of the Centaurus cluster\(^8\) (Taylor et al. 2002; Rudnick & Blundell 2003; Ensslin et al. 2003; Taylor et al. 2007).

There are three distinct scenarios we consider (but see Burn 1966) when using Faraday rotation to probe the properties of a magnetized, thermal plasma.

1. The diffuse polarized synchrotron emission from the lobes is mixed with the magnetized, thermal (Faraday rotating) plasma. In this case, the emission from the back of the source will have been rotated more than the emission from the front of the source and so “depth depolarization” can occur along any line of sight. In addition, “beam depolarization” can occur due to variations in RM on scales smaller than the observing beam. In the former situation, (i.e., not applicable to beam depolarization) the concept of Faraday depth is introduced. Accurate determination of Faraday depth is complex, but necessary to extract information on the magnetic field and thermal density within the source (Cioffi & Jones 1980). Radio galaxy lobes embedded in clusters or groups are often used to probe the cluster/group medium (Dreher et al. 1987; Clarke et al. 2001; Eilek & Owen 2002; Taylor et al. 2002; Laing et al. 2008). Here, one must first show that the rotating plasma arises purely from the foreground medium itself rather than the lobes or skin of the radio source (Rudnick & Blundell 2003).

2. The polarized emission is diffuse and located behind the Faraday rotating plasma. This is similar to the above scenario in terms of beam depolarization, however no depth depolarization occurs because there is no mixing of the emitting and rotating regions. For example, extended radio galaxies could be used to directly probe Galactic magnetic fields.

3. The polarized emission is unresolved and located behind the magnetized, thermal (Faraday rotating) plasma. In this scenario, all the polarized signals from any element of the background source are rotated by the entire line of sight through the screen. The screen can cause spatial depolarization due to variations in RM in the screen across the angular size of the source. This probes scale sizes in the screen on scale sizes smaller than the background source size. No depth depolarization occurs. This technique is often used to investigate the magnetic structure of the Milky Way (Brown et al. 2003, 2007; Mao et al. 2008), nearby galaxies (Han et al. 1998; Gaensler et al. 2005), and galaxy clusters (Kim et al. 1991; Hennessy et al. 1989).

Note that scenarios 2 and 3 above are not affected by back versus front differences such as the Laing–Garrington effect (Laing 1988; Garrington et al. 1988).

The typical angular size subtended by radio galaxy lobes is too small to include a statistically significant number of compact polarized background sources, at least for the source densities reached with current sensitivity (typically mJy beam\(^{-1}\)). Hence, up until now, all studies of the Faraday rotation in radio galaxy lobes have been restricted to using emission from the lobes themselves, as in scenario 1 above (recent examples include Kharb et al. 2009; Laing et al. 2008). The outer lobes of the nearest radio galaxy, Centaurus A, subtend a large enough angular size (\( \approx45\text{ deg}^2 \)) that hundreds of polarized sources are detected along sightlines behind them. For the first time, we can investigate the magnetized plasma in radio lobes—using scenario 3—without the complexities added by depth and beam depolarization effects. This is the basis for the analysis presented in this paper.

We have recently completed a large spectropolarimetric imaging campaign at 1.4 GHz with the Australia Telescope Compact Array (ATCA) and the Parkes 64 m radio telescope, to image in full the polarized structure of the nearest radio galaxy, Centaurus A. The full spectropolarimetric images of Centaurus A from ATCA and Parkes data combined will be reported in a subsequent paper (I. J. Feain et al. 2010, in preparation). An additional result of the ATCA component of the observations, we have also observed in full polarization 1005 compact radio sources in the background of Centaurus A: some along lines of sight through the lobes and some along lines of sight beyond (outside) the boundaries of the radio lobes. In this paper, we present a catalog of these 1005 compact radio sources. RMs and polarized flux densities are presented for a subset (281) of the sources. We investigate the spatial correspondence between the radio lobes of Centaurus A and the both the distributions of RMs and fractional polarization of the background sources.

This paper is divided into sections in the following way: Section 2 describes the ATCA radio continuum observations and Section 3 outlines the calibration and data processing procedures. In Section 4, we define the procedure used for source finding, give the format for the source catalog and provide the URL where the entire catalog can be accessed. Section 5 describes the RM Synthesis technique with which we derived reliable RMs and polarized flux densities for 281 out of the 1005 sources cataloged. In Section 6, we show the RM distribution and briefly compare the total and polarized intensity source counts from our data with total and polarized intensity source counts from the literature. We also compute a lower limit on the very small scale RM fluctuations from the lobes of Centaurus A. Section 7 presents a detailed investigation into the spatial variations in the ensemble of 281 Faraday RMs. We fit and subtract out the Milky Way foreground RM component leaving a residual excess RM dispersion on angular scales \( \theta \sim 0:3 \). We model this excess as possibly arising from a thin skin around the southern giant radio lobe. Finally, our concluding remarks are given Section 8. We adopt a distance to Centaurus A of 3.8 Mpc from Rejkuba (2004). At 3.8 Mpc, 1° corresponds to \( \approx66 \text{ kpc} \).

### 2. OBSERVATIONS

The data used in this paper were obtained as part of a larger (∼45 deg\(^2\)) radio synthesis imaging survey of Centaurus A (NGC 5128), the nearest active galaxy in the universe.

The ATCA was used in mosaic mode over four epochs between 2006 December and 2008 March to observe a total field of view covering \( 5°\times9° \) (in 406 pointings) and centered on R.A. (J2000) 13\( ^h25\min27\sec, \) decl. (J2000) –43°01′09″. The standard continuum correlator configuration was employed for the observations at all epochs. This correlator configuration (FULL_128_2) was chosen because it allows dual-frequency observations using 2\times128 MHz bandwidth observing windows split into 32 channels (the spectral resolution is 1.77 channels).
per window. We centered the two frequency windows on 1344 and 1432 MHz; used in this way, the two windows overlap by 40 MHz and the total usable bandwidth is 192 MHz. Observations were carried out with four complementary array configurations, each with a maximum baseline of 750 m. The ATCA’s linearly polarized feeds measure cross-polarization data which allowed us to derive the four relevant Stokes parameters (I, Q, U, V). The temporal variations in the atmospheric phase were tracked with a two minute observation of PKS B1316−46 about once an hour. In addition, the parallactic angle coverage of PKS B1316−46 was sufficient to enable us to solve for the polarization leakages in each 12 hr observing block. PKS B1934−638 was observed once a day and used both to correct for the instrumental bandpass and derive the absolute flux density scale. On average, each of the 406 pointings in the mosaic received 100–120 minutes integration.

3. DATA CALIBRATION AND POST-PROCESSING

The data were inspected for radio frequency interference (RFI) and flagged accordingly using root-mean-square (rms)-based flagging in the automated RFI detection algorithm PFEFLAG (Middelberg 2006). Approximately, 5% and 30% of our visibilities at 1384 and 1432 MHz, respectively, were flagged. Each baseline and channel was then visually inspected and, where residual RFI was evident, manually flagged. MIRIAD was used in the standard way to derive and apply the instrumental bandpass, gain, phase, and absolute flux density calibration. The typical level of polarization leakage in an individual pointing was ∼0.1% at the phase center, ∼0.5% at the half-power point, and ∼1.7% at 0.1 power. The off-axis polarization leakage of the ATCA is reduced substantially by the combination of mosaicing and tracking a source over a wide range of parallactic angles; we measured the leakage across the calibrated final mosaic to be ∼0.1%. After calibration and disregarding the edge channels, there were 24 × 8 MHz channels between 1296 and 1480 MHz. Faraday RMs were derived across the full 24-channel band. The ionospheric variations in RM above the ATCA over the Faraday RMs were derived across the full 24-channel band. There were 24 and tracking a source over a wide range of parallactic angles; we were tracked with a two minute observation of PKS B1316−638 was observed once a day and used both to correct for the instrumental bandpass and derive the absolute flux density scale. On average, each of the 406 pointings in the mosaic received 100–120 minutes integration.

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Table 1

| Parameter       | Continuum | Stokes (Q, U) |
|-----------------|-----------|---------------|
| Bandwidth (MHz) | 192       | 8 per channel |
| σ (mJy beam⁻¹)  | 0.15      | 0.5 per channel |
| θmaj × θmin    | 63′′ × 33′′ | 63′′ × 33′′ |
| Position angle  | 3°        | 3°           |

Note. Position angle is defined with north 0° and east +90°.

A mask was applied to the spatially filtered data set in order to create an image with a roughly uniform sensitivity; the point-source sensitivities for the final continuum image as well as the individual 8 MHz Stokes Q and U images are given in Table 1. Figure 1 shows the mask that was applied to the spatially filtered image: the large blanked region in the center of the mosaic is due to high-residual sidelobes around the very bright (Speak ∼ 7.5 Jy beam⁻¹ at 1.4 GHz) central region of Centaurus A. The two smaller blanked regions south of the Centaurus A core are associated with the residual sidelobes of two bright background sources (PKS 1320−446 and PMN J1318−4620). The edge of the mosaic was also masked to remove elevated noise levels (≥0.3 mJy beam⁻¹), where primary beam correction was significant. Figures 2 and 3 show the continuum intensity and corresponding linear polarized intensity (not corrected for Ricean bias) for a representative portion of the surveyed area. Figure 1 has a roughly uniform sensitivity that is given in Table 1. The total survey area, after masking, is 33.93 deg².

4. SOURCE FINDING

Source detection was performed using the MIRIAD routine SFINX (Hopkins et al. 2002) on the total intensity image in Figure 1. We ran SFINX in its original mode, which uses a “Search and Destroy” algorithm much the same as the AIPS task VSAD, to find all sources in the image and fit them with a gaussian. This extracted an initial list of candidate sources with a peak flux density greater than 3 mJy beam⁻¹ (20σ). To obtain more accurate fits than those produced by SFINX we then ran the MIRIAD task IMFIT to do a constrained gaussian fit (restricting the fit to a small region around the object) for each source detected in the initial candidate list. We ran this iteratively, subtracting each fitted source from the image, to produce a residual map. We identified poor fits by comparing the rms noise in a small region around the source in the original image and in the residual map. Cases in which the rms noise increased after the fitted source was subtracted from the image were investigated further. Sources with poor fits and sources with multiple components are identified as such in the catalog. The final catalog consists of 1005 compact sources to a detection threshold of 3 mJy beam⁻¹. The associated error in the peak flux density for each source has been estimated by the quadrature sum of the rms noise in the image and the uncertainty in transferring the flux scale of the ATCA primary calibrator PKS B1934−638 (1%−2%⁹). The error in the integrated flux density, ΔI, for each source was estimated, using Equation (16) in Condon (1997) to be

\[ ΔI = ΔA \times \frac{I}{A}, \]

where A is the peak flux density. The format of the catalog in Table 2 is the following.

9 See ATNF Technical Memo AT/39.3/040.
Figure 1. Masked, spatially filtered total intensity radio continuum image of the Centaurus A field used to find and catalog the compact radio sources given in Table 2. The gray shading shows the regions of our field that we used for source finding. In these regions, many of the compact radio sources can be seen. Masked regions, shown in white, correspond to areas where the sensitivity of the image is poorer, in the vicinity of very bright sources (both the core of Centaurus A as well as two foreground sources with flux densities > 2 Jy in the southern lobe) or near the edge of the mosaic where primary beam correction was significant. The contours correspond to a Parkes 1.4 GHz image at 14' resolution (courtesy Mark Calabretta) with levels 1.5, 2, 2.5, 3, 4, 5, 6, 10, 100 Jy beam$^{-1}$.

The horizontal-striped region beyond the edge of the mask that does not contain point sources is beyond the observed mosaic. The image is shown projected in a sin coordinate system.

Column 1: source name.
Columns 2 and 3: right ascension and declination in J2000 coordinates.
Columns 4 and 5: peak flux density averaged over the full bandwidth in units of mJy/beam and its associated error.
Columns 6 and 7: integrated flux density averaged over the full bandwidth in units of mJy and its associated error.
Columns 8–10: fitted major and minor axis and position angle from IMFIT
Columns 11–13: deconvolved major and minor axis and position angle from IMFIT

5. POLARIZATION AND FARADAY ROTATION MEASURE

The polarized fluxes and Faraday RMs were derived for 281 of the 1005 cataloged sources listed in Table 2 as follows.

At each source position in Table 2, we extracted the Stokes $Q$ and $U$ values and their expected rms error (based on the sensitivity of the map at that position) in each of the 24 independent spectral channels in our data set. Converting from frequency to $\lambda^2$, where $\lambda$ is the observing wavelength of each channel, we then have a dependence of the complex Stokes vector ($Q$, $U$) as a function of $\lambda^2$ at the peak position of each source. For pure Faraday rotation, this vector should have a phase that varies linearly with $\lambda^2$ at a rate equal to the source’s RM. We extracted this RM from each data set via RM synthesis (Brentjens & de Bruyn 2005; Heald et al. 2009), in which we compute the Fourier transform of the complex Stokes vector to yield the amplitude of the polarized flux, $P$, as a function of Faraday depth, $\phi$. For a source with a single valued RM, the RM synthesis spectrum will have a single peak whose height is equal to the polarized flux, and width (RM resolution) determined by the wavelength coverage of the observation. The
polarization position angle is given by the $Q$ and $U$ values at the peak polarized emission. This method achieves signal to noise corresponding to the full bandwidth of the observation, but with bandwidth smearing effecting only the individual channel width. Any deviations from $\lambda^2$ behavior resulting from complex Faraday rotation structure over the background source are seen as structure in the RM synthesis spectrum.

This analysis was applied to all 1005 sources in Table 2, with the individual ($Q$, $U$) measurements weighted by the inverse square of the sensitivity for each spectral channel. The total bandwidth and spectral resolution of our data mean that the FWHM in Faraday depth for a single RM component is 280 rad m$^{-2}$, and that we are sensitive to RMs with magnitudes less than $\approx 3500$ rad m$^{-2}$. The resulting Faraday depth functions exhibit spectral sidelobes because of incomplete wavelength coverage (in the same way that an aperture synthesis image shows sidelobes because of incomplete $u$–$v$ coverage). Since we can compute the RM transfer function for each source (i.e., the Faraday depth spectrum of a source of unit polarized intensity and zero RM), we can deconvolve our data set using the same iterative CLEAN approach routinely applied to radio interferometric images (Högberg 1974). Specifically, we have implemented RMCLEAN, as described by Heald et al. (2009).

When the above prescription is applied to all sources, we now have 1005 deconvolved spectra of $P$ (in units of mJy beam$^{-1}$) as a function of $\phi$ (in units of rad m$^{-2}$). Some examples are shown at varying signal to noise in Figure 4.

For each source, we identified the peak value of $P$ as a function of $\phi$, and then applied a parabolic fit around this peak to yield the best-fit estimate of the polarized flux and RM. We then debiased the polarized flux by estimating the observed rms noise, $\sigma_{QU}$, in the real and imaginary parts of the spectrum far from the peak, and subtracting $\sigma_{QU}$ in quadrature from the peak value of $P$ (see Simmons & Stewart 1985). The ratio of the debiased polarized flux to the noise then yields the signal-to-noise ratio ($S/N$) of the detection of Faraday rotation. We adopted a threshold $S/N \geq 7$ as a minimum criterion for a reliable RM determination (see, e.g., Figure 9 of Brentjens & de Bruyn 2005). For sources with polarized fluxes above this threshold, we computed the uncertainty in RM as the FWHM of the RM transfer function divided by twice the $S/N$.

Of the 1005 cataloged continuum radio sources, 281 (28%) polarized sources were robustly detected according to the detection criteria described above and are listed in Table 3. The format of Table 3 is as follows.

### Column 1: source name.

### Columns 2 and 3: right ascension and declination in J2000 coordinates.

### Columns 4 and 5: peak polarized flux density (after correction for the Ricean bias) in units of mJy/beam and its associated $S/N$.

### Columns 6 and 7: measured Faraday RM and its associated uncertainty derived using RM synthesis and RM CLEAN in units of rad m$^{-2}$.

Figure 5 shows the distribution in the total intensity to polarized intensity plane of the 281 sources in our sample whose debiased polarized intensities have a $S/N \geq 7$. The dashed, diagonal lines represent lines of constant fractional polarization.

### 5.1. Which Sources are Behind the Lobes?

For much of the rest of this paper, we wish to analyze separately the polarized sources located behind the lobes of...
Centaurus A from polarized sources whose sightlines pass outside of the lobes. The latter are used as a control sample and to model and subtract the RM component from the Milky Way. We define what constitutes behind the radio lobes to correspond to an "edge" where, at 1.4 GHz and 14' resolution, the surface brightness of the lobes drops below 1.5 Jy beam\(^{-1}\); this is the last contour in Figures 1 and 7. At approximately this value, the surface brightness of the lobes decreases sharply (but there is clearly still diffuse emission from the lobes present, probably out to the edges of our mosaic). Using a 1.5 Jy beam\(^{-1}\) threshold, 121 out of the total 281 RMs are behind the radio lobes with the remaining 160 RMs along sightlines outside the lobes. We have tested the sensitivity of our results to the exact value of the boundary chosen for inside versus outside the lobes. We are

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
Source & R.A. (J2000) & Decl. (J2000) & \(P\) & S/N & RM & \(\Delta\text{RM}^a\) & \(\text{RM}_{\text{corr}}^b\) \\
 & hh:mm:ss.ss & dd:mm:ss.s & (mJy beam\(^{-1}\)) & & (rad m\(^{-2}\)) & (rad m\(^{-2}\)) & (rad m\(^{-2}\)) \\
\hline
133515−381451 & 13:36:21.99 & -46:48:08.28 & 6.20 & 89.2 & 47.7 & 1.6 & 18.1 \\
133515−381451 & 13:35:58.13 & -41:02:03.12 & 8.77 & 108.0 & -66.6 & 1.3 & -25.3 \\
133527−452406 & 13:30:27.55 & -45:24:06.12 & 8.06 & 84.7 & -62.3 & 1.6 & -3.6 \\
133533−461211 & 13:25:53.71 & -46:21:21.96 & 7.79 & 94.7 & -42.2 & 1.5 & 24.0 \\
133800−452717 & 13:38:00.26 & -45:27:17.64 & 7.66 & 116.6 & -40.7 & 1.2 & 12.3 \\
133912−443649 & 13:19:21.77 & -44:36:49.68 & 7.52 & 67.4 & -73.0 & 2.1 & -24.7 \\
133924−450802 & 13:32:41.71 & -45:08:02.04 & 7.52 & 101.9 & -80.6 & 1.4 & -7.9 \\
134145−403618 & 13:21:45.46 & -40:36:18.36 & 6.53 & 90.1 & -71.2 & 1.5 & -22.4 \\
134001−413824 & 13:30:01.15 & -41:38:24.00 & 6.42 & 51.5 & -53.2 & 2.7 & -8.0 \\
134287−464808 & 13:28:27.74 & -46:48:08.28 & 6.20 & 89.2 & -47.7 & 1.6 & 18.1 \\
135753−461330 & 13:22:53.52 & -46:13:30.72 & 6.12 & 71.9 & -57.7 & 1.9 & 10.4 \\
133746−451641 & 13:37:46.54 & -45:16:41.52 & 6.05 & 69.6 & -56.8 & 2.0 & -4.3 \\
133159−401343 & 13:13:50.95 & -41:01:34.32 & 6.02 & 29.6 & -67.0 & 4.7 & -9.4 \\
133160−444944 & 13:16:30.31 & -44:49:44.76 & 5.79 & 72.8 & -97.9 & 1.9 & -29.5 \\
133107−465745 & 13:31:07.06 & -46:57:45.36 & 5.57 & 69.8 & -18.9 & 2.0 & 45.4 \\
\hline
\end{tabular}
\caption{Catalog of the 281 Polarized Radio Sources Detected}
\end{table}

Notes. The columns in this table are described in Section 5. The table below gives the brightest 20 sources in linear polarized intensity; the full list of 281 radio sources is available electronically from Vizier (http://vizier.u-strasbg.fr).

\(^a\) The associated uncertainty in RM does not include the uncertainty due to ionospheric variations which are \(\leq 1\) rad m\(^{-2}\).

\(^b\) RMs after correcting for the Galactic contribution.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
confident that our result is robust for all contour values that we tested as boundaries (which were between 1 and 2 Jy beam$^{-1}$).

6. RM DISTRIBUTION AND SOURCE COUNTS

6.1. RM Distribution

A histogram of the distribution of the full RM sample is shown in the top panel of Figure 6. The mean RM of the total distribution is $-57$ rad m$^{-2}$ with a standard deviation of 30 rad m$^{-2}$. These values are in good agreement with earlier observations of the Faraday RM of the lobe emission of Centaurus A reported to vary from $-40$ to $-70$ rad m$^{-2}$ across the source (Cooper et al. 1965; Clarke et al. 1992). Other studies have also reported an average RM for Centaurus A of $-59 \pm 3$ rad m$^{-2}$ (Gardner & Davies 1966; Simard-Normandin et al. 1981). The RM of Centaurus A is typical of that measured for other nearby sources which implies that the RM is dominated by a foreground component (Johnston-Hollitt et al. 2004; Short et al. 2007). The middle and bottom panels of Figure 6 show histograms of the RM distributions of sources behind and outside the lobes of Centaurus A, as defined in Section 5.1.

Examination of the available RM sky data from interpolated maps (Johnston-Hollitt et al. 2004; Frick et al. 2001) shows that Centaurus A is embedded in a large region of negative RM of average value $\sim -27$ rad m$^{-2}$ with a slope of roughly $-0.9$ rad m$^{-2}$ per degree in longitude and $-0.6$ rad m$^{-2}$ per degree in latitude over the region corresponding to these observations. Unfortunately, the paucity of RM data in the southern hemisphere means interpolated values in this region have been inferred from some of the most sparse data distributions in the entire sky.

6.2. Source Counts

We have compared our total and linearly polarized intensity source counts as a function of flux to published source counts in order to confirm that our sample is statistically comparable to other samples in the literature and that Centaurus A in the foreground is not affecting the global statistics of the sample. We find the following.

1. Our derived total intensity source counts are consistent, within the errors, with the continuum source counts from the NRAO VLA Sky Survey (NVSS; Condon et al. 1998).
2. Our polarized intensity source counts (in the flux range $0.5$ mJy $\leq P \leq 14$ mJy) are consistent within the errors with the polarized source counts from the ELAIS N1 field (in the flux range $0.5$ mJy $\leq P \leq 20$ mJy) reported by Taylor et al. (2007).

6.3. A Limit on Small Scale Turbulence in the Lobes

Random fluctuations in either $B_0$ or in $n_e$ on some angular scale $R$ will increase the dispersion in RM determined on this same scale. If $R$ is smaller than the resolution element used to probe the fluctuations, then this effect will lead to “beam” depolarization where the “beam” size is the angular scale of the background polarized sources. Such small-scale RM fluctuations have been inferred in the Galactic plane (Haverkorn et al. 2008) and the Large Magellanic Cloud (Gaensler et al. 2005) using an ensemble of extragalactic polarized sources.

We find no significant difference in the polarized source counts for the 121 sources behind the radio lobes of Centaurus A compared with the 160 sources outside the lobes. The lack of detection corresponds to a limit on magnetized thermal structure in the lobes of Centaurus A on scales much smaller than the median angular scale size of the background sources themselves; this is $\sim 10''$ for a 10 mJy source at 1.4 GHz (Windhorst et al. 1984). The mean fractional polarization of the 121 polarized sources behind the lobes (quoted with the standard error in the mean) is $7.6\% \pm 0.5\%$ compared to the mean fractional polarization for the sources outside the lobes of $7.3\% \pm 0.4\%$. Using the Burn (1966) law for depolarization,

$$ f_d = e^{-2\sigma_{RM} \lambda^4}, $$

we find that the polarization of the 121 sources behind the lobes is $7.6\% \pm 0.5\%$ and the polarization of the 160 sources outside the lobes is $7.3\% \pm 0.4\%$. Note that we analyze those polarized sources with a S/N $\geq 7$ only; there are polarized sources below this S/N cutoff but we do not consider them in this study.
In this section, we are interested in separating the Milky Way RM component from any RM component that is intrinsic to the radio lobes of Centaurus A. Although it is not possible to do this for the RM of an individual source, it is possible to isolate the Milky Way and Centaurus A RM contributions in a statistical sense, subject to the assumption that the statistics of the Milky Way spatial RM fluctuations on small scales (less than a few degrees) do not change appreciably across the field. To do this, we use the 160 RMs that are not located along sightlines through the radio lobes (Section 5.1) to fit for the foreground Milky Way component. This was achieved using the MIRIAD task IMPOPT to fit a first order polynomial to the RM surface in two dimensions. This surface was then subtracted from all 281 RMs. In this way, we have essentially also removed the Milky Way RM component from the RMs located behind the radio lobes of Centaurus A.

7.3. The Turbulent Component

The difference between the standard deviation of the foreground-subtracted RMs behind the lobes compared to outside the lobes (3.8 rad m$^{-2}$), if real, implies structure/turbulent magnetized plasma in the lobes. To verify and quantify this difference, we have compared the amplitude of the RM fluctuations as a function of angular separation in the lobes (or around the edges of the lobes) to a “control group” of RMs located on sightlines outside the lobes using an approach based on the structure function,

$$D_{\text{RM}}(\theta) = \langle |\text{RM}(\theta + \theta') - \text{RM}(\theta')|^2 \rangle,$$  

(4)
where $\theta$ is the angular separation between sources. The structure function is a robust and reliable means of measuring RM fluctuations (Simonetti et al. 1984). In comparison with other statistical techniques like an autocorrelation function analysis for example, the structure function is far less susceptible to uncertainties in the mean RM level and to large-scale RM gradients, on scales below those comparable to the size of the gradient. A structure function-based analysis is also immune to the irregular spatial sampling of our RMs.

### 7.2.1. Rotation Measure Structure Functions

Prior to forming structure functions for sources behind and outside the lobes, the large-scale RM component from the foreground Milky Way was fitted and subtracted, as described above. When we compared the structure function formed from the foreground-corrected RMs to the structure function formed from the observed RMs (i.e., with no foreground subtraction applied), we found no significant difference between the two results for scales below $\approx 4^\circ$. This is unsurprising because the large-scale gradients are expected to affect the structure function on scales comparable to the scale of the gradient only.

RM differences, as probed by a structure function, can arise from intrinsic differences in the radio sources themselves, or due to spatial variations in the foreground (i.e., in the Galaxy or in the lobes of Centaurus A). Figures 8(a) and (b) are the RM structure functions for sources located behind and outside the radio lobes of Centaurus A, respectively. It is clear from a comparison of Figures 8(a) and (b) that the RMs behind the lobes have excess structure on scales $0.2^\circ \lesssim \theta \lesssim 4^\circ$. The point at the smallest angular scale, $\theta = 0.025$, is determined solely on the basis of RM differences between each of the double sources in our sample. Since many of these double sources are likely to be the lobes of an individual galaxy, variations in RMs between the double sources is likely to be much lower than intrinsic variations between independent sources. Thus the jump in amplitude due to the fact that the latter set is necessarily determined using independent sources, with independent intrinsic RMs. The variation in the intrinsic (internal) RMs of independent sources contributes a “white-noise” component to the RM variability, which manifests itself as an offset in the amplitude at all points $\theta > 0.075$. From the definition of the structure function in Equation (4), it can be easily shown that the difference of two structure functions is equal to the structure function of all sources behind the northern lobe subtracted from the RM structure function of all sources behind the southern lobe.

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

**Figure 8.** RM structure functions of (a) the 121 polarized sources located behind the radio lobes of Centaurus A and (b) the 160 polarized sources located along sightlines outside the radio lobes of Centaurus A. (c) The difference between (a) and (b).

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

**Figure 9.** (a) RM structure function of the sources that are located north of $\delta = -43^\circ$ subtracted from the RM structure function of all sources that are located south of $\delta = -43^\circ$. (b) The structure function of all sources outside the lobes that are located north of $\delta = -43^\circ$ subtracted from the RM structure function of all sources outside the lobes that are located south of $\delta = -43^\circ$. (c) The RM structure function of all sources behind the northern lobe subtracted from the RM structure function of all sources behind the southern lobe.

(A color version of this figure is available in the online journal.)
due to RM fluctuations associated with the southern lobe of Centaurus A. Figure 9(a) compares the RM structure function of all the polarized sources that are located south of declination $-43^\circ$ to all the polarized sources located north of declination $-43^\circ$. There is a clear strong north–south asymmetry present in the data, indicating an excess of RM structure in sources in the south relative to those in the north. Figure 9(b) compares all sources that are outside the lobes and located south of $\delta = -43^\circ$ to all sources located outside the lobes and north of $\delta = -43^\circ$. Figure 9(b) shows no evidence for a north–south asymmetry outside the lobes. Figure 9(c) compares sources located inside the southern lobe to those inside the northern lobe. Here, again the asymmetry between the lobes is apparent but the significance is degraded by the smaller number of sources within each lobe. Taken together, Figures 9(a)–(c) suggest that the north–south asymmetry is due to variations between the northern and southern lobes of Centaurus A, and not due to the Milky Way.

Note that the source density in each region is accounted for in determining the error bars associated with that structure function and does not otherwise systematically bias the structure function.

7.3. Physical Interpretation of the Lobe RM

The total and polarized intensity structure of Centaurus A correlates very well with the RM variations of the background sources (I. J. Feain et al. 2010, in preparation; Junkes et al. 1993). Such a correlation could not occur if the RM structure is unrelated to Centaurus A itself. For example, Junkes et al. (1993) investigated the polarized structure of Centaurus A at 6.3 cm and showed there is a striking difference in the polarized intensity structure between the northern and southern lobes. The polarized emission in the northern lobe largely follows the continuum emission uniformly down to the sensitivity limits of the survey. There is little evidence for depolarization in the northern lobe. The emission in the southern lobe, however, is depolarized (Gardner & Whiteoak 1971) and chaotic with position angle jumps of up to 90° in places. Between $\delta = -44^\circ45'$ and $\delta = -45^\circ45'$ (J2000 coordinates), the southern lobe becomes highly chaotic and turbulent (see Figure 3(b) in Junkes et al. 1993). The good spatial coincidence between the depolarization of the southern lobe and that of the RM signal in the background sources on angular scales between $0.2 < \theta < 4.0$ inside the lobes gives us confidence that the depolarizing (rotating) medium is intrinsic to the southern radio lobe of Centaurus A.

The amplitude of the RM signal in Figure 8(c) is approximately 620 rad$^2$ m$^{-4}$, implying that the southern lobe of Centaurus A contribute an RM signal with an rms $\sigma_{\text{RM}} \approx 17$ rad m$^{-2}$ on an angular scale $\sim 0.3$ (20 kpc at the distance to Centaurus A). This RM signal could arise either from a thin skin around the lobe or a turbulent medium throughout the lobe. Our data are not sufficient to confidently distinguish between these two possibilities, but we tend to favor the former (thin skin) based on the location of the maximum dispersion of RMs seen in Figure 7 being well aligned with total intensity features along the western boundary of the southern lobe (I. J. Feain et al. 2010, in preparation) which look like surface-wave instabilities. We model this signal as follows.

Suppose that the edge of the southern lobe has uniform thermal density, $n_{\text{th}}$, and a coherent magnetic field, $B_0$, with angle of orientation, $\theta_0$, which changes direction randomly on a spatial scale of $l \sim 20$ kpc. Then, following Gaensler et al. (2001), the dispersion of the RMs produced by uniformly polarized emission passing through the edge of the southern lobe is given by

$$\sigma_{\text{RM}} \approx \frac{810}{\sqrt{3}} \left( \frac{n_{\text{th}}}{\text{cm}^{-3}} \right) \left( \frac{B_0}{\mu \text{G}} \right) \sqrt{\frac{D}{\text{kpc}}} \left( \frac{l}{\text{kpc}} \right).$$

where $D = 180$ kpc is the estimated path length through the edge of the lobe. To estimate $n_{\text{th}}$, we assume mixing occurs between the lobe magnetic field and the Centaurus intra-group medium due to Kevin–Helmholtz instabilities (Bicknell et al. 1990). Based on the ram pressure stripping arguments to explain gas depletion in dwarf galaxies in the Centaurus group, Bouchard et al. (2007) infer an intragroup medium density near Centaurus A of $n_e \approx 10^{-3}$ cm$^{-3}$; note however that based on X-ray observations, Feigelson et al. (1981) estimate a similar density for the interstellar medium of NGC 5128 itself out to 9 kpc. Substituting $\sigma_{\text{RM}}, D$ and $l$ into Equation (5) results in $B_0 \approx 0.8 n_{\text{th}}^{-1} \mu \text{G}$, where $n_{\text{th}} = n_1 10^{-3}$ cm$^{-3}$.

The possible existence of a magneto-ionic skin around the edges of Centaurus A—a low power Fanaro–Riley class I (FR I) source (Fanaro & Riley 1974)—with RM fluctuations on scales of 20 kpc, is not dissimilar to that inferred for skins around the lobes of the powerful FR II sources PKS 2104–25N and Cygnus A (Bicknell et al. 1990; Cameron 1988). In the latter two cases, the RM signals are between 10 and 100 times larger than that seen in Centaurus A, which is not unexpected given both sources are located at or near the centres of clusters where the intracluster density will be higher, possibly by several orders of magnitude.

8. CONCLUSION

In this paper, we have presented the results of a 1.4 GHz spectropolarimetric imaging survey of 34 deg$^2$ centered on the nearest radio galaxy Centaurus A. A catalog of the 1005 background, compact radio sources brighter than 3 mJy beam$^{-1}$ has been made available in electronic format.

We used Faraday RM synthesis to measure linear polarized intensities and RMs for each source in our sample. There were 281 sources, out of 1005 in total, with a S/N $\geq 7$ in linear polarized intensity and for these we also publish a table of polarized intensities and RMs. The density of RMs published here, 8.3 per deg$^2$, represents the densest RM grid known to date. Of the 281 RMs, 121 come from sources located behind the radio lobes of Centaurus A; the remaining 160 being from sources located along sightlines outside (in projection) the radio lobes.

The continuum source counts and the linear polarized intensity ($P$) source counts (for sources with S/N $\geq 7$ in $P$) are consistent with published source counts giving us confidence that our sample is statistically robust and the emission from the lobes of Centaurus A has not contaminated the global statistics of our sample. There is no measurable difference between the polarized source counts behind the lobes and those outside the lobes. We derived an upper limit on the very small scale turbulence in the lobes of $<10$ rad m$^{-2}$ on scales $<180$ pc. This is similar to the limit derived on the volume-averaged RM signal from the lobes.

We modeled the Milky Way contribution to the RMs by fitting a first-order polynomial surface to the 160 RMs along sightlines outside the lobes of Centaurus A and subtracting this surface from all 281 RMs in our sample. The residual RMs behind the lobes have a mean of $-4.5 \pm 2.8$ rad m$^{-2}$ and a
standard deviation of 30.4 rad m$^{-2}$, compared to a mean of $-1.6 \pm 2.1$ rad m$^{-2}$ and standard deviation of 26.6 rad m$^{-2}$ for RMs outside the lobes. Assuming a magnetic field strength in the lobes of 1.3 $B_l$ $\mu$G, we derived an upper limit to the uniform thermal plasma density in the lobes of $(n_e) < 5 \times 10^{-5}$ $B_l$ cm$^{-3}$. This is a factor of 2–3 times smaller than previously published limits and further constrains the prospects for high-energy acceleration processes in the lobes of Centaurus A.

We used a structure function analysis to measure an excess RM dispersion in the southern lobe of Centaurus A of $\sigma_{RM} \approx 17$ rad m$^{-2}$ on angular scales of $\sim 0.3$ arcmin associated with the southern lobe of Centaurus A. The RM signal is modeled as possibly arising from a thin skin with a thermal plasma density equivalent to the Centaurus intragroup medium density and a coherent magnetic field that reverses its sign on a spatial scale of 20 kpc. If the Centaurus intragroup density is of order $10^{-3}$ cm$^{-3}$, the skin magnetic field strength is of order $1 B_l$. If $n_e$ is of order an magnitude smaller, $B_l$ will be $10 \times$ larger.

A more sensitive survey of the southern lobe is now required to verify if the RM signal is associated with the entire southern lobe, or a thin skin (sheath) around the edges, although the latter seems more likely. In addition, a deep X-ray observation of the edge of the southern lobe would be incredibly revealing in terms of the detailed physics it could probe. The southern lobe of Centaurus A has typically been neglected in favor of investigations of the northern lobe; this is almost certainly because of the very interesting northern middle lobe (NML) region (there has been no southern counterpart to the NML detected). In this paper, we have shown that the edge of the giant southern lobe, rather than any part of the giant northern lobe, is probably associated with fluctuating RMs on scales of 20 kpc. It is extremely timely now to follow-up this region with a multiwavelength campaign at, in particular, X-ray and deep narrow-band optical wavelength regimes. We are currently completing a detailed analysis of the full polarization radio continuum images of Centaurus A at a resolution of $\approx 40''$. In this analysis, we will be able to compare the fluctuating RM region with the polarized and total intensity structure of the lobes at a factor of about 5 times the resolution that has been previously possible. If our model of a thin skin is correct, these new images should reveal the signatures of surface waves around the lobes, which would be evidence of mixing between the lobe emission and the Centaurus intragroup medium.

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