Erratum: “A View through Faraday’s Fog 2: Parsec Scale Rotation Measures in 40 AGN” (2004, ApJ, 612, 749)

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An error in the typesetting of the dates of the polarization angle calibration observations was present in Table 2. There was also an error in Table 2 for the position angle \(\chi\) of the 22 GHz VLA polarization angle. This incorrect \(\chi\) was plotted in Figure 1. The difference between the two position angles is 0°.7. Using the correct value of the 22 GHz VLA polarization angle for the integrated rotation measure confirms our previous result for the integrated rotation measure of the electric vector position angle (EVPA) calibrator, 3C 279 of 31 ± 10 rad m\(^{-2}\). There is no impact on the EVPA calibration and no results in Zavala & Taylor (2004) are changed as a result of this erratum. Corrected versions of Table 2 and Figure 1 are presented in this erratum.

![Figure 1. EVPA calibration vs. \(\lambda^2\) for 3C 279. Filled circles are VLA polarization monitoring data, and open boxes are the VLBA EVPA’s after the turns derived from Table 2 were applied. The solid line represents a least-squares fit for a Faraday rotation \(\lambda^2\) law to the VLA data including the 5 GHz position angle (not shown). The fit represents an integrated RM of 31 ± 10 rad m\(^{-2}\).](image-url)
Table 2
EVPA Calibration using 3C 279

| Telescope | Freq. GHz | Date       | Pol. Flux mJy | χ° Deg. |
|-----------|-----------|------------|---------------|---------|
| UMRAO     | 8.0       | 2001 Jun 20| 2044          | 56.6    |
|           | 14.5      | 2001 Jun 25| 2058          | 60.5    |
| VLA       | 5.0       | 2001 Jun 24| 1297          | 64.0    |
|           | 8.5       | 2001 Jun 24| 1995          | 58.2    |
|           | 22        | 2001 Jun 24| 2016          | 56.3    |
|           | 43        | 2001 Jun 24| 1889          | 57.0    |
| VLBA      | 8.5       | 2001 Jun 21| 1894          | 34.0    |
|           | 15.15     | 2001 Jun 21| 2147          | −66     |

Note.
° χ for VLBA is before applying the EVPA calibration derived from the VLA data.

Reference

Zavala, R. T., & Taylor, G. B. 2004, ApJ, 612, 749
A VIEW THROUGH FARADAY’S FOG. II. PARSEC-SCALE ROTATION MEASURES IN 40 ACTIVE GALACTIC NUCLEI

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ABSTRACT

Results from a survey of the parsec-scale Faraday rotation measure (RM) properties for 40 quasars, radio galaxies, and BL Lac objects are presented. Core RMs for quasars vary from approximately 500 to several thousand rad m⁻². Quasar jets have RMs that are typically 500 rad m⁻² or less. The cores and jets of the BL Lac objects have RMs similar to those found in quasar jets. The jets of radio galaxies exhibit a range of RMs from a few hundred to almost 10,000 rad m⁻² for the jet of M87. Radio galaxy cores are generally depolarized, and only one of four radio galaxies (3C 120) has a detectable RM in the core. Several potential identities for the foreground Faraday screen are considered, and we believe the most promising candidate for all the active galactic nucleus types considered is a screen in close proximity to the jet. This constrains the path length to approximately 10 pc, and magnetic field strengths of approximately 1 µG can account for the observed RMs. For 27 out of 34 quasars and BL Lac objects, their optically thick cores have good agreement with a λ² law. This requires the different τ = 1 surfaces to have the same intrinsic polarization angle independent of the observed frequency and distance from the black hole.

Subject headings: galaxies: active — galaxies: ISM — galaxies: jets — galaxies: nuclei — radio continuum: galaxies

Online material: machine-readable table

1. INTRODUCTION

The first rotation measure (RM) toward an extragalactic radio source was published by Cooper & Price (1962). They discussed the potential for such measurements as a probe of the Galactic Faraday screen. Wardle (1977) analyzed radio polarization monitoring observations of compact extragalactic sources for signs of Faraday rotation. He suggested that the combined Faraday rotation from our Galaxy and the host object were relatively small. Observations on arcsecond scales of 555 steep-spectrum sources by Simard-Normandin et al. (1981) and of flat-spectrum sources by Rudnick & Jones (1983) and Rusk (1988) all confirmed this result. An expectation was established using these observations that the unresolved parsec-scale cores of active galactic nuclei (AGNs) would similarly show negligible Faraday rotation. It was not until simultaneous multifrequency polarimetry became available with the Very Long Baseline Array (VLBA) that these expectations were met. Extreme parsec-scale rest-frame RMs were first reported for OQ 172 (Udomprasert et al. 1997; 40,000 rad m⁻²) and 3C 138 (Cotton et al. 1997; 5300 rad m⁻²). Such RMs show that interpretations of polarization observations on parsec scales in AGNs require simultaneous determination of the RM. Without knowledge of the RM in a source, the orientations of the polarization vectors in the relativistic jets of AGNs are uncertain. For example, an RM of 250 rad m⁻² will change the intrinsic polarization angle of a source by 25° at 8 GHz. The existence of RMs in quasar cores of 1000 rad m⁻² or more (Taylor 1998, 2000) and the time variability of RMs in quasar cores (Zavala & Taylor 2001) show how essential knowledge of the RM is for the correct interpretation of the observed polarization.

Michael Faraday first observed what we now refer to as Faraday rotation when he passed polarized light through glass in the presence of a magnetic field (Faraday 1933). He correctly surmised that this observation hinted at the connection between electric and magnetic fields and light. Light subject to Faraday rotation will have its intrinsic polarization angle χ₀ rotated to an observed angle χ by

$$\chi = \chi_0 + \text{RM} \lambda^2,$$

where λ is the observed wavelength. The linear relationship to λ² is the characteristic signature of Faraday rotation. The slope of the line is known as the rotation measure (RM) and depends linearly on the electron density nₑ, the net line-of-sight magnetic field B₀, and the path length dl through the plasma. Using units of cubic centimeters, milligauss, and parsecs, the RM is given by

$$\text{RM} = 812 \int n_e B_0 dl \text{ rad m}^{-2}.$$
8.1 and 15.2 GHz using the 10 element VLBA. This 24 hr observation targeted the sources listed in Table 1. Because of an electrical short in the elevation system, the Fort Davis antenna was lost for the first 7.5 hr of the 24 hr run. Prior to self-calibration, all processing was performed in the Astronomical Image Processing System (AIPS; van Moorsel et al. 1996). AIPS procedures described in Ulvestad et al. (2001) were employed and are indicated by eight-letter capitalized words (e.g., VLBACPOL). Data collected at elevations less than 10° were flagged. Amplitude calibration was performed with the task APCAL. An opacity correction was employed at all frequencies, as several antennas (Pie Town, Fort Davis, Kitt Peak, and Hancock) reported rain during the observation. Plots of $T_{\text{sys}}$ versus air mass also indicated a variable opacity at North Liberty. The procedure VLBAPANG corrected the observations for varying parallactic angles of the altitude-azimuth–mounted VLBA antennas. VLBAMPCL was used on 2 minutes of data from 3C 279 to remove errors due to clock and correlator model inaccuracies. A global fringe fit was run on all the data to remove the remaining delay and rate errors with the procedure VLBAFRNG. VLBAFRNG uses the AIPS task FRING, an implementation of the Schwab-Cotton algorithm (Schwab & Cotton 1983). The delay offset between the right and left circularly polarized data was removed using the procedure VLBAPCL (Cotton 1993). A bandpass correction table was made with BPASS using 1741–038 as a bandpass calibrator. The data were then averaged in frequency across the individual intermediate frequencies (IFs).

Self-calibration was done using DIFMAP (Shepherd 1997; Shepherd et al. 1994) and AIPS in combination. Considerable radio frequency interference was present at 12 GHz on almost all baselines for 3C 279 and 3C 446 and was edited out. This resulted in the loss of 49% of the visibilities for 3C 279 and 23% for 3C 446 at 12 GHz. As the gain curves of the antennas used in the amplitude calibration are poorly known at 12 GHz, we compared the VLBA flux at 12 GHz with that from the VLA/VLBA Polarization Calibration Web page (Taylor & Myers 2000) and with data from the University of Michigan Radio Astronomy Observatory (UMRAO; H. Aller 2003, private communication). This comparison suggested that a reduction of approximately 10% in the gain solution was required at 12 GHz, and this was applied with the task SNCOR. Table 1 lists the number of scans on each source, as well as the rms and peak flux in the 15 GHz Stokes I map that this calibration produced. Scans were 3.5 minutes long. If all 10 antennas are present in seven scans, the expected thermal noise at 15 GHz is approximately 0.5 mJy beam$^{-1}$.

Polarization leakage of the antennas (D-terms) were determined using the AIPS task LPCAL (Leppänen et al. 1995). We chose 0552+398 as the D-term calibrator, as it had a wide parallactic angle coverage and a simple and nearly unresolved polarization structure. Plots of the real versus imaginary cross-hand polarization data indicated that a satisfactory D-term solution was obtained. This was also verified in plots of the real and imaginary cross-hand data versus ($u$, $v$) parallactic angle. After applying the D-term solution, no variation was seen as a function of ($u$, $v$) parallactic angle.

Absolute electric vector position angle (EVPA) calibration was determined by using the EVP3 of 3C 279 listed in the VLA Polarization Monitoring Program. We used the integrated $Q$- and $U$-fluxes from the VLBA data to derive a position angle, which we compared with that listed on the Polarization Calibration Web page. This calibration scheme rests on the assumption that most of the polarized flux observed by the Very Large Array (VLA) is seen with the VLBA. To verify this, the polarized fluxes observed by UMRAO, the VLA, and the VLBA are listed in Table 2 for 8 and 15 GHz, with their respective observation dates. The good agreement between these sources.

### Table 1: Target Sources

| Source (1) | Name (2) | Identification (3) | Magnitude$^a$ (4) | $z$ (5) | $S_{15}$ (6) | Scans (7) | $\sigma_{15\,\text{GHz}}$ (8) | Peak$_{15\,\text{GHz}}$ (9) |
|-----------|----------|-------------------|-------------------|--------|-------------|-----------|----------------|------------------------|
| 0202+149  |          | Q                 | 22.1              | 0.41   | 2.29        | 8         | 0.4            | 1.52                   |
| 0336–019  | CTA 26   | Q                 | 18.4              | 0.85   | 2.23        | 9         | 0.5            | 2.01                   |
| 0355+508  | NRAO 150 | EF                | ...              | ...    | 3.23        | 7         | 3.4            | 6.40                   |
| 0458–020  |          | Q                 | 18.4              | 2.29   | 2.33        | 9         | 0.3            | 0.91                   |
| 0552+398  | DA 193   | Q                 | 18.0              | 2.37$^b$ | 5.07        | 7         | 1.2            | 3.02                   |
| 0605–085  |          | Q                 | 18.5              | 0.87   | 2.80        | 7         | 0.8            | 1.10                   |
| 0736+017  |          | Q                 | 16.5              | 0.19   | 2.58        | 7         | 0.4            | 1.31                   |
| 0748+126  |          | Q                 | 17.8              | 0.89$^b$ | 3.25        | 7         | 0.3            | 1.27                   |
| 1055+018  |          | BL                | 18.3              | 0.89   | 2.15        | 11        | 0.8            | 4.03                   |
| 1253–055  | 3C 279   | Q                 | 17.8              | 0.54   | 21.56       | 7         | 2.2            | 8.81                   |
| 1546+027  |          | Q                 | 18.0              | 0.41   | 2.83        | 8         | 0.4            | 1.53                   |
| 1548+056  |          | Q                 | 17.7              | 1.42   | 4.05        | 8         | 1.3            | 1.68                   |
| 1741–038  |          | Q                 | 18.6              | 1.05   | 4.06        | 7         | 2.1            | 4.32                   |
| 1749+096  |          | BL                | 16.8              | 0.32   | 5.58        | 7         | 0.6            | 2.54                   |
| 2021+317  |          | EF                | ...              | ...    | 2.02        | 9         | 0.3            | 0.356                  |
| 2201+315  |          | Q                 | 15.5              | 0.30   | 3.10        | 10        | 0.3            | 2.01                   |
| 2223–052  | 3C 446   | Q                 | 17.2              | 1.40   | 3.92        | 8         | 1.5            | 4.74                   |

Notes:—Col. (1): B1950.0 source name. Col. (2): Alternate common name. Col. (3): Optical identification from the literature (NED), with Q for quasar, BL for BL Lac object, and EF for empty field. Col. (4): Optical magnitude. Col. (5): Redshift. Col. (6): Total flux density at 15 GHz measured by Kellermann et al. (1998). Col. (7): Number of scans. Col. (8): rms (mJy beam$^{-1}$) in the 15 GHz untapered map. Col. (9): Peak flux (Jy) in the 15 GHz untapered map.

$^a$ Note that many sources are highly variable.

$^b$ Redshift questionable, see Wills & Wills (1976).
values for telescopes with very different resolutions makes us confident in our absolute EVPA calibration. The position angles for 3C 279 were observed with the VLA in B-configuration on 2001 June 24. These position angles were in good agreement with nearly contemporaneous observations from the UMRAO data for 3C 279. The EVPA calibration at 8 GHz was directly obtained from the polarization calibration Web site. Polarization monitoring observations at 8 and 22 GHz were interpolated to produce position angles at 12 and 15 GHz, assuming the EVPAs obeyed a $\lambda^2$ Faraday rotation law. Figure 1 shows the final calibrated VLBA EVPAs with the VLA EVPAs from the Polarization Calibration Web page.

The uncertainty in the EVPA calibration using the RM fit in Figure 1 is approximately $\pm 1^\circ$. To this uncertainty we add in quadrature the uncertainty derived from the individual Stokes $Q$ and $U$ maps. There is some additional uncertainty from the lack of simultaneous VLA polarization observations that is difficult to quantify. Data obtained with UMRAO and the VLA to establish the EVPA calibration were taken within 1–5 days of the VLBA observation. If the lack of simultaneous observations by the VLA and/or UMRAO were significant, we would expect all the fits to a $\lambda^2$ law to require a systematic increase in their error budget. Although some sources do not show good agreement with a $\lambda^2$ law, many do, and thus we conclude that the errors have been properly accounted for.

To perform the RM analysis, data cubes in $\lambda^2$ were constructed. The upper and lower pairs of 12 GHz IFs and all four 15 GHz IFs were averaged to improve the signal-to-noise ratio and to obtain long and short spacings in $\lambda^2$. Final frequencies used for the RM analysis are shown in Table 3. This provides adequate short and long spacings in $\lambda^2$ to properly recover RMs between $\pm 30,000$ rad m$^{-2}$. The 12 and 15 GHz images used to produce the polarization angle maps were tapered to approximate the 8 GHz resolution, and a restoring beam matched to the 8 GHz beam was used. All images are naturally weighted.

3. RESULTS

Maps showing the RM, RM-corrected electric vectors, and spectral index between 8.5 and 12.1 GHz are presented. If the fits to a $\lambda^2$ law do not appear satisfactory, a reduced $\chi^2$ test is performed. If the reduced $\chi^2$ indicates that a $\lambda^2$ law is ruled out at a 3 $\sigma$ level or higher, we remove the source from consideration when examining the RM properties of the sample as a whole (§ 4).

3.1. B0202+149

This object was depolarized at 12 and 8 GHz, and thus no RM image is provided. The object is classified as a blazar at a redshift of 0.405 (Perlman et al. 1998). Observations of superluminal motion (Pyatunina et al. 2000), a brightness temperature in excess of $10^{12}$ K (Moellenbrock et al. 1996), and the
high probability of detection with EGRET (Mattox et al. 1997) all agree with a blazar identification for this source. This is surprising, as unlike other blazars such as 3C 279 and BL Lac (Zavala & Taylor 2003 and references therein), there is no detectable RM in 0202+149. This is the case for another EGRET-detected blazar, 0420–014 (Zavala & Taylor 2003), whose depolarization seems to be explained by the superposition of components of differing position angles. For 0202+149 this may be the case. The source is only detected in polarization in Stokes U at 15 GHz, and a full-resolution image (Fig. 2) shows two components of Stokes U of opposite sign and different magnitude. The negative U-component is only weakly detected. Tapering and restoring with a beam matched to the 8 GHz resolution nearly eliminates the polarized components of 0202+149 at 15 GHz.

3.2. B0336–019

This source has an RM of $-2547 \pm 33$ rad m$^{-2}$, which decreases to $281 \pm 37$ rad m$^{-2}$ (Fig. 3 [left]). A sharp border between the negative slope to the RM in the core and the positive slope in the jet coincides with a change in the intrinsic electric vector direction, as shown in Figure 3 (right). This change in the slope of the RM and electric vector orientation occurs as the spectral index changes from positive to negative (Fig. 4).

The quality of the fits to a $\chi^2$ law for this quasar appears suspect (Fig. 3 [left]). The reduced $\chi^2$ of the fits are 7.7 or larger. With 5 degrees of freedom this implies that a $\chi^2$ law can be ruled out with a confidence of more than 3 $\sigma$.

Fig. 2.—Full-resolution 15 GHz Stokes U-flux in gray scale overlaid on Stokes I contours at 15 GHz for B0202+149. Contours start at 1.2 mJy beam$^{-1}$ and increase by factors of 2.

Fig. 3.—Left: RM image (color) for 0336–019 overlaid on Stokes I contours at 15 GHz. The inset is a plot of EVPA $\chi$ (degrees) vs. $\chi^2$ (cm$^2$). Right: Electric vectors (1 mas $= 67$ mJy beam$^{-1}$ polarized flux density) corrected for Faraday rotation overlaid on Stokes I contours. Contours start at 1.5 mJy beam$^{-1}$ and increase by factors of 2.
3.3. B0355+508

Also known as NRAO 150, this source has no optical counterpart, and thus no redshift is available. The RM in the core is $-1034 \pm 21$ rad m$^{-2}$, and this decreases by approximately a factor of 5 ($-216 \pm 65$ rad m$^{-2}$) in the jet component (Fig. 5 [left]). The core and jet have very different electric vector orientations (Fig. 5 [right]), but it should be noted that the signal in the jet component is fairly weak, as can be seen in the inset EVPA versus $\chi^2$ plot in Figure 5 (left). As Figure 6 shows, the core is optically thick, while the jet component is optically thin.

The 8 GHz core EVPA values suggest a nonlinear variation of $\chi$ with $\chi^2$. However, the reduced $\chi^2$ for the core cannot rule out a Faraday rotation law at a level of 3 $\sigma$ or higher, and we therefore conclude that the core of B0355+508 adheres to the $\chi^2$ law. The reduced $\chi^2$ for the RM fits in the jet can rule out a $\chi^2$ at a level of 3 $\sigma$ or more, and we conclude that the data for the jet are not consistent with the $\chi^2$ law.

3.4. B0458–020

Figure 7 (left) shows that the fits to a $\chi^2$ law are not very convincing for this source. The RM of $-582 \pm 32$ rad m$^{-2}$ has a reduced $\chi^2$ of 12. The 3 $\sigma$ confidence level with 5 degrees of freedom is approximately 3.1, and we reject the $\chi^2$ law for the core of B0458–020. Similarly, we reject the $\chi^2$ law for the jet, as the reduced $\chi^2$ is 6. Assuming Faraday rotation does apply to B0458–020, we see in Figure 7 (right) that the jet and core have nearly the same electric vector alignments. B0458–020 has an optically thick core and optically thin jet (Fig. 8).

3.5. B0552+398

O’Dea et al. (1990) classify 0552+398 as a gigahertz peaked spectrum source. Infrared imaging suggests it is an interacting galaxy in a dense cluster (Hutchings et al. 1999). Wills & Wills (1976) note that the redshift of 0552+398 is uncertain because of a lack of firmly identified spectral lines.

We are just able to resolve an RM gradient across this source, as shown in Figure 9 (left). The RM changes from $338 \pm 39$ to $165 \pm 45$ rad m$^{-2}$. This gradient is across a projected distance of 20 pc. This distance would incorporate the high RM core and lower RM jet in 3C 273 shown in Zavala & Taylor (2001). The 8–15 GHz RM image of 3C 273 in Zavala & Taylor (2001) showed lower RMs than the higher resolution 15–43 GHz RM images. Therefore, a much higher RM may be hidden under the coarse spatial resolution of our image. RM-corrected electric vectors are aligned east-west (Fig. 9 [right]). The spectral index changes from approximately 0 in the north to $-0.5$ or less in the south (Fig. 10).

3.6. B0605–085

The core and jet component 4 mas east of the core show similar RMs, although there is a lower signal-to-noise ratio at the higher frequencies for the jet component (Fig. 11 [left]). The inset plots in Figure 11 (left) have RMs of 364 $\pm 20$ and 287 $\pm 57$ rad m$^{-2}$. About 2 mas southeast of the core there seems to be a flattening of the RM slope, and this is coincident with a change in the RM-corrected EVPA (Fig. 11 [right]). Figure 12 shows that this region 2 mas from the core marks the transition to a negative spectral index.

As the signal-to-noise ratio for the RM fit in the jet appears rather low, we examined the reduced $\chi^2$ for both the jet and core RM fits. The core RM fits all have a reduced $\chi^2$ consistent with a $\chi^2$ law with values less than the 3 $\sigma$ level. Even the apparently poor RM fit in the jet has a reduced $\chi^2$ of 2.1 and is thus consistent with a $\chi^2$ law interpretation.

3.7. B0736+017

This quasar has recently been shown to exhibit a dramatic optical flare and shows evidence for microvariability (Clements et al. 2003). The weakly polarized core (0.6%) has an RM of 469 $\pm 40$ rad m$^{-2}$ (Fig. 13 [left]), but approximately 50% of the pixels within a beam area centered on the core have a reduced $\chi^2$, which rules out a $\chi^2$ law at a level greater than 3 $\sigma$. We thus reject the optically thick (Fig. 14) core as a region where the Faraday rotation law applies. Beyond a beamwidth ({$\approx$}1 mas west) from the core, the reduced $\chi^2$ values are consistent with a $\chi^2$ law, and the spectrum changes to optically thin 2–3 mas west of the core (Fig. 14).

3.8. B0748+126

A typical quasar core RM of 1433 $\pm$ 34 rad m$^{-2}$ and a jet RM consistent with 0 (23 $\pm$ 40 rad m$^{-2}$) are shown in Figure 15 (left). These two RM regions have EVPAs that differ by $\approx$45° (Fig. 15 [right]). Figure 16 shows the typical flat-spectrum core and steep-spectrum jet. Wills & Wills (1976) report an uncertainty in the published redshift.

3.9. B1055+018

An error in the observing schedule caused the loss of the 15 GHz data for 1055+018, so the total intensity contours in Figures 17 and 18 are for 12.5 GHz. Table 4 shows that the core of this BL Lac object is relatively weakly polarized at 8.1 GHz, and the core and jet RMs ($-77 \pm 25$ and $6 \pm 73$ rad m$^{-2}$) are
Fig. 5.—Left: RM image (color) for 0355+508 overlaid on Stokes I contours at 15 GHz. The inset is a plot of EVPA $\chi$ (degrees) vs. $\lambda^2$ (cm$^2$). Right: Electric vectors (1 mas = 67 mJy beam$^{-1}$ polarized flux density) corrected for Faraday rotation overlaid on Stokes I contours. Contours start at 6.9 mJy beam$^{-1}$ and increase by factors of 2.

Fig. 6.—Spectral index $\alpha_{12}$ plot for 0355+508 overlaid on Stokes I contours at 15 GHz. Contours start at 6.9 mJy beam$^{-1}$ and increase by factors of 2.
Fig. 7.—Left: RM image (color) for 0458−020 overlaid on Stokes $I$ contours at 15 GHz. The inset is a plot of EVPA $\chi$ (degrees) vs. $\lambda^2$ (cm$^2$). Right: Electric vectors ($1 \text{ mas} = 25 \text{ mJy beam}^{-1}$ polarized flux density) corrected for Faraday rotation overlaid on Stokes $I$ contours. Contours start at 1.4 mJy beam$^{-1}$ and increase by factors of 2.

Fig. 8.—Spectral index $\alpha_{12,1}^{B_1}$ plot for 0458−020 overlaid on Stokes $I$ contours at 15 GHz. Contours start at 1.4 mJy beam$^{-1}$ and increase by factors of 2.
consistent with 0. Approximately 50% of the pixels have a reduced $\chi^2$, which is not consistent with a $k^2$ law. For the same reason we reject the $k^2$ law for the jet of 1055+018.

The core is optically thick, and the jet component 9 mas northwest of the core is optically thin. The jet does not exhibit the interesting "spine and sheath" polarization structure found by Attridge et al. (1999) at 5 GHz. Our observations probably lack the sensitivity to reveal the sheath structure that Attridge et al. observed.

3.10. 3C 279

This paper presents the fifth epoch of RM monitoring for the quasar 3C 279. Previous epochs were presented in Taylor (1998, 2000) and Zavala & Taylor (2001, 2003). The core RM (Fig. 19 [left]) is $-166 \pm 19$ rad m$^{-2}$, and component C4 (4 mas west of the core) has an RM of $86 \pm 21$ rad m$^{-2}$. The RM-corrected EVPA (Fig. 19 [right]) of the core is 50$^\circ$, and for C4 it is 76$^\circ$. Within a milliarcsecond of the core the spectral index becomes negative (Fig. 20).

3.11. B1546+027

A gradient in RM is visible across 1548+056 from south to north in Figure 23 (left). Three mas south of the peak the RM is

3.12. B1548+056

A gradient in RM is visible across 1548+056 from south to north in Figure 23 (left). Three mas south of the peak the RM is
$-259 \pm 27$ rad m$^{-2}$, while 3 mas north of the peak the RM has declined to $44 \pm 59$ rad m$^{-2}$. This occurs over a projected distance of less than 60 pc. The RM-corrected electric vectors maintain a roughly constant orientation across the source (Fig. 23 [right]). There is a flat spectral index along the RM gradient, as shown in Figure 24.

3.13. B1741$-038$

B1741$-038$ was one of the first three sources detected with a space VLBI experiment (Levy et al. 1986). This quasar is essentially unresolved (Fig. 25 [left]) and has a core RM of $223 \pm 20$ rad m$^{-2}$. The RM-corrected electric vectors are oriented along a southeast-northwest axis (Fig. 25 [right]). The spectrum steepens from south to north, as shown in Figure 26.

3.14. B1749+096

The BL Lac object 1749+096 has a fairly uniform RM distribution. The fits in the inset plots of Figure 27 (left) have RMs of $145 \pm 24$ and $97 \pm 25$ rad m$^{-2}$, which are essentially the same within the errors. The RM-corrected electric vectors appear roughly perpendicular to the projected direction of the jet (Fig. 27 [right]). B1749+096 is dominated by a flat-spectrum core (Fig. 28); thus, the magnetic vectors are parallel to the electric vectors (Aller 1970) in Figure 27 (right).

3.15. B2021+317

This source lacks an optical counterpart and has an RM consistent with 0 ($-31 \pm 21$ rad m$^{-2}$) in Figure 29 (left). The NRAO VLA Sky Survey (Condon et al. 1998) image shows a jet extending 2′ to the northeast, an extreme misalignment with the structure seen on parsec scales. The jet has a very diffuse and poorly ordered structure. The RM-corrected electric vectors are oriented east-west (Fig. 29 [right]). The core is optically thick (Fig. 30), and the magnetic vectors are therefore parallel to the electric vectors in Figure 29 (right).

3.16. B2201+315

There is a sign change in the slope of the RM across the core of this quasar from $-1628 \pm 36$ to $612 \pm 36$ rad m$^{-2}$ (Fig. 31 [right]). RM-corrected electric vectors appear in Figure 31 [right]. The 12 and 15 GHz position angles in the core do not appear to follow the slope set by the 8 GHz position angles. This may result from optical depth effects, as the core
is optically thick (Fig. 32). Nearly half of the pixels of the core have a reduced $\chi^2$ greater than the 3 $\sigma$ level. Beyond 2 mas southwest from the core, the RM fitted $\chi^2$ values do become consistent with a $\chi^2$ law. Four mas southwest of the core, the RM has decreased to 5 ± 33 rad m$^{-2}$, consistent with 0.

3.17. 3C 446

3C 446 could be a transition object between quasar and BL Lac objects (Falomo et al. 1994), but the case for a quasar identification has also been made by Bregman et al. (1986, 1988). In Figure 33 (left) the RM decreases from 492 ± 23 rad m$^{-2}$ west of the core to 100 ± 22 rad m$^{-2}$ east of the core. This gradient in RM tracks a change in the RM-corrected electric vector direction of almost 60° (Fig. 33 [right]). 3C 446 has a flat, optically thick spectrum throughout its RM distribution (Fig. 34). The jet, which has no detected polarized flux, is optically thin.

4. DISCUSSION

To characterize the RM distribution of the various sources we consider the RM value of the cores of the AGNs presented here. Figure 35 shows the histogram of the observed core RM in 200 rad m$^{-2}$ bins. Although this is the RM at a single pixel, it is generally representative of the values found in the flat-spectrum cores of the individual AGNs. As expected, there is no preference for the sign of the RM, and the mean RM observed is 137 rad m$^{-2}$. The sparse sampling prevents a reliable determination of the distribution function, but the general appearance is consistent with a zero-mean Gaussian distribution.

To understand the magnitude of the parsec-scale RM effect, we determined the average of the absolute value of the observed core RM. This average absolute value, 644 rad m$^{-2}$, is approximately twice the maximum of about 300 rad m$^{-2}$ expected on larger angular scales from the observed RMIs in Simard-Normandin et al. (1981).

4.1. RM and Radio Luminosity

Our understanding of AGNs is based largely on an empirical foundation that suggests a differentiation based on luminosity (Lawrence 1987). We attempt to test for this differentiation by plotting the rest-frame core RM versus 15 GHz radio luminosity in Figure 36. The cosmology used is $\Omega_m = 0.23$, $\Omega_{vac} = 0.77$, and $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$. We made use of E. L. Wright’s online cosmology calculator to determine the luminosity distance and allowed for relativistic beaming by using a unit solid angle. Figure 36 looks like a scatter plot, but an interesting fact emerges. The multipoch data for 3C 279 show that the RM is relatively insensitive to luminosity. At a given radio luminosity, 3C 279 has high and low RMs. Whatever causes the change in RM in the core of 3C 279 does not require large changes in the radio luminosity.

The intrinsic RM and radio luminosity are both redshift-dependent properties. Therefore, a false correlation is expected in Figure 36. As the plot resembles a scatter plot, the false correlation from plotting two redshift-dependent quantities versus each other does not appear significant. To quantify this, we used the ASURV, version 1.2, statistics package (Lavalley et al. 1992). We used the Cox and generalized Kendall $\tau$ tests (Isobe et al. 1986) to test for a radio luminosity–intrinsic RM correlation. The Cox test gives the probability of no correlation at the 20% level, and the Kendall $\tau$ test rules out a
Fig. 15.—Left: RM image (color) for 0748+126 overlaid on Stokes I contours at 15 GHz. The inset is a plot of EVPA $\chi$ (degrees) vs. $J^2$ (cm$^2$). Right: Electric vectors (1 mas = 17 mJy beam$^{-1}$ polarized flux density) corrected for Faraday rotation overlaid on Stokes I contours. Contours start at 1.2 mJy beam$^{-1}$ and increase by factors of 2.

Fig. 16.—Spectral index $\alpha_{12.1}$ plot for 0748+126 overlaid on Stokes I contours at 15 GHz. Contours start at 1.2 mJy beam$^{-1}$ and increase by factors of 2.
Fig. 17.—*Left:* RM image (color) for 1055+018 overlaid on Stokes $I$ contours at 12.5 GHz. The inset is a plot of EVPA $\chi$ (degrees) vs. $j^2$ (cm$^2$). *Right:* Electric vectors (1 mas = 25 mJy beam$^{-1}$ polarized flux density) corrected for Faraday rotation overlaid on Stokes $I$ contours. Contours start at 2.4 mJy beam$^{-1}$ and increase by factors of 2.

Fig. 18.—Spectral index $\alpha_{12}^{8.1}$ plot for 1055+018 overlaid on Stokes $I$ contours at 12.5 GHz. Contours start at 2.4 mJy beam$^{-1}$ and increase by factors of 2.
correlation at the 5% level. We conclude that there is no correlation between the intrinsic RM and radio luminosity, even though one might be expected.

4.2. Fractional Polarization Properties

Faraday rotation by a foreground screen can produce beam depolarization (Gardner & Whiteoak 1966). Longer wavelengths will exhibit this effect to a higher degree because of the $\chi^2$ nature of Faraday rotation. Figure 37 (left) shows the 15 GHz core fractional polarization versus observed RM for the sources in Table 4. There is a lack of sources with high core fractional polarization and high observed RM. This distinction is somewhat more pronounced at 8 GHz, as seen in Figure 37 (right). In Zavala & Taylor (2003) we noted that an

| SOURCE | NAME | ID | z | Peak | Integ. | PeakPOL | Peak | Integ. | PeakPOL | RM$^0$ | $R_c^0$ | $m_c^0$ | RM$^i$ |
|--------|------|----|---|------|--------|---------|------|--------|---------|-------|--------|--------|-------|
| 0133+476 | DA 55 | Q | 0.86 | 2921 | 3103 | 55 | 3736 | 3802 | 50 | −1410 | 0.941 | 1.88 | 0.983 | −4878 |
| 0202+149 | | Q | 0.41 | 1664 | 2016 | <1.9 | 1648 | 1869 | 3 | ... | 0.825 | <1.1 | 0.882 | ... |
| 0212+735 | | Q | 2.37 | 2229 | 3125 | 39 | 1844 | 2445 | 41 | −542 | 0.713 | 1.75 | 0.754 | 2.22 |
| 0356–019 | CTA 26 | Q | 0.85 | 1447 | 1919 | 15 | 2191 | 2512 | 28 | ... | 0.754 | 1.04 | 0.873 | 1.28 |
| 0355+508 | | EF | ... | 4631 | 5479 | 16 | 7001 | 7245 | 3 | ... | 0.825 | <1.1 | 0.966 | 1.80 |
| 0415+397 | 3C 111 | G | 0.05 | 861 | 1963 | <2.0 | 1537 | 2263 | <1.8 | ... | 0.439 | <2.3 | 0.679 | <1.2 |
| 0420–014 | | Q | 0.92 | 2035 | 2377 | 7 | 2644 | 2872 | 6 | ... | 0.856 | 0.34 | 0.921 | 0.23 |
| 0430+052 | 3C 120 | G | 0.03 | 1075 | 3307 | <2.1 | 797 | 2519 | 4 | 2082 | 0.325 | <1.5 | 0.316 | 3.8 |
| 0458–020 | | Q | 2.29 | 668 | 858 | 3 | 931 | 1055 | 13 | ... | 0.779 | 0.45 | 0.882 | 1.40 |
| 0528+134 | | Q | 2.06 | 2924 | 3479 | 11 | 3100 | 3439 | 32 | −163 | 0.840 | 0.38 | 0.901 | 1.03 |

Notes.—Table 4 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content. Col. (1): B1950.0 source name. Col. (2): Alternate common name. Col. (3): Optical identification from the literature (NED), with Q for quasar, BL for BL Lac object, and EF for empty field. Col. (5): 8.11 GHz peak flux density (mJy beam$^{-1}$). Col. (6): 8.11 GHz sum of CLEAN components (mJy). Col. (7): 8.11 GHz polarized flux density (mJy beam$^{-1}$) at location of peak. Cols. (8)–(10): Same as for cols. (5)–(7), for 15.1 GHz. Col. (11): Observed core RM (rad m$^{-2}$). Col. (12): 8.11 GHz core dominance. Col. (13): 8.11 GHz core fractional polarization (%). Cols. (14)–(15): Same as cols. (12)–(13), for 15.1 GHz. Col. (16): Core rest-frame RM (rad m$^{-2}$).

a Zavala & Taylor 2001.
b Taylor 2000.
c Taylor 1998.
d Agreement with $\chi^2$ law ruled out based on reduced $\chi^2$.  

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**FIG. 19.—**Left: RM image (color) for 3C 279 overlaid on Stokes $I$ contours at 15 GHz. The inset is a plot of $\chi$ (degrees) vs. $\chi^2$ (cm$^2$). Right: Electric vectors (1 mas = 250 mJy beam$^{-1}$ polarized flux density) corrected for Faraday rotation overlaid on Stokes $I$ contours. Contours start at 5.3 mJy beam$^{-1}$ and increase by factors of 2.
RM gradient of 770 rad m$^{-2}$ across a beam is sufficient to cause substantial depolarization at 8 GHz. To more quantitatively account for the observed fractional polarization, the beam depolarization can be modeled in the same manner as depolarization due to internal Faraday rotation (Gardner & Whiteoak 1966). The observed fractional polarization is a sinc function of the RM. By fixing $k^2$ and varying the RM we can plot the expected beam depolarization, but this requires setting an amplitude to the sinh function at zero RM. We set this amplitude at 10%, in agreement with the maximum observed fractional polarization at 8 GHz for this small sample. This is similar to the maximum core fractional polarization at 5 GHz found for 106 quasars by Pollack et al. (2003). In Figure 37 (left and right) the solid line plots the expected beam depolarization using the equation

$$m(\%) = 10 \left| \frac{\sin(RM \lambda^2)}{RM \lambda^2} \right|, \quad (3)$$

as derived by Burn (1966). This is a simple model of a constant gradient across the beam. Figure 37 (right) appears to agree with the expected 8 GHz beam depolarization. The 15 GHz fractional polarization data seem to respond to the expected depolarization more strongly. The first null in fractional polarization for 15 GHz in this simple model is not expected to occur until an RM gradient of almost 8000 rad m$^{-2}$, yet the fractional polarization is 2% or less at 2000 rad m$^{-2}$. This indicates that the real situation is more complicated than a constant RM gradient in a foreground screen.

Tribble (1991) put forth a modification to the treatment of Burn by considering variations in the RM that are comparable to the resolution of the telescope. His results increase the fractional polarization as compared to the Burn model, and so would not help a foreground gradient to explain both the 8 and 15 GHz fractional polarization data.

Surprisingly, the maximum core fractional polarizations of our 8 GHz data presented here, and at 5 GHz from Pollack et al. (2003), are higher than the 6% found by Lister (2001) at 43 GHz. One might expect that the decreased depolarization and lower blending of components at 43 GHz would yield higher core fractional polarizations than observed at lower frequencies.

Multipoch monitoring of the RM structure in 3C 279 allows us to revisit the idea of a luminosity-RM correlation. Figure 38 shows the results from 5 years of RM data for the core of the quasar 3C 279. The solid line in Figure 38 shows the observed core RM versus epoch. The 8 and 15 GHz core fractional polarization are shown as dashed and dash-dotted lines, respectively. What is immediately evident is the anticorrelation between the core fractional polarization at 8 and 15 GHz and the observed core RM. From Table 4 we see that the highest RMs and lowest fractional polarizations occur when the quasar has the highest radio luminosity. This can also be seen in the optical monitoring data taken at Foggy Bottom Observatory of Colgate University (Balonek & Kartaltepe 2002; T. Balonek & J. Kartaltepe 2004, in preparation). From 1997 January to 2001 June, 3C 279 brightened from an $R$ magnitude of 15.5 to 13.6, reaching almost to magnitude 12.5 by 2001 August. Superposed on this trend is considerable variability on timescales of days, as well as microvariability. Overinterpreting the better time-sampled optical light curve should be discouraged, but a relation between the radio and optical luminosity and the varying RM deserves further scrutiny.

4.3. Identification of the Faraday Screen

Faraday rotation serves as a probe of the physical conditions responsible for the observed rotation, but this is only useful if the screen can be identified. We first consider and rule out several locations in order of increasing distance from the supermassive black hole. We then make the argument that the screen is located close to the relativistic jet itself.
Fig. 21.—Left: RM image (color) for 1546+027 overlaid on Stokes I contours at 15 GHz. The inset is a plot of EVPA \( \chi \) (degrees) vs. \( \lambda^2 \) (cm\(^2\)). Right: Electric vectors (1 mas = 67 mJy beam\(^{-1}\) polarized flux density) corrected for Faraday rotation overlaid on Stokes I contours. Contours start at 1.2 mJy beam\(^{-1}\) and increase by factors of 2.
Fig. 22.—Spectral index $\alpha_{1.1}^{15}$ plot for 1546+027 overlaid on Stokes $I$ contours at 15 GHz. Contours start at 1.2 mJy beam$^{-1}$ and increase by factors of 2.
Fig. 23.—Left: RM image (color) for 1548+056 overlaid on Stokes I contours at 15 GHz. The inset is a plot of EVPA $\chi$ (degrees) vs. $\chi^2$ (cm$^2$). Right: Electric vectors (1 mas = 50 mJy beam$^{-1}$ polarized flux density) corrected for Faraday rotation overlaid on Stokes I contours. Contours start at 2.4 mJy beam$^{-1}$ and increase by factors of 2.
Fig. 24.—Spectral index $\alpha^{15}_{22}$ plot for 1548+056 overlaid on Stokes $I$ contours at 15 GHz. Contours start at 2.4 mJy beam$^{-1}$ and increase by factors of 2.
Fig. 25.—Left: RM image (color) for 1741–038 overlaid on Stokes $I$ contours at 15 GHz. The inset is a plot of EVPA $\chi$ (degrees) vs. $\lambda^2$ (cm$^2$). Right: Electric vectors (1 mas = 100 mJy beam$^{-1}$ polarized flux density) corrected for Faraday rotation overlaid on Stokes $I$ contours. Contours start at 5.4 mJy beam$^{-1}$ and increase by factors of 2.
Fig. 26.—Spectral index $\alpha_{15}$ plot for 1741–038 overlaid on Stokes $I$ contours at 15 GHz. Contours start at 5.4 mJy beam$^{-1}$ and increase by factors of 2.
Fig. 27.—Left: RM image (color) for 1749+096 overlaid on Stokes $I$ contours at 15 GHz. The inset is a plot of EVPA $\chi$ (degrees) vs. $j^2$ (cm$^2$). Right: Electric vectors ($1\text{ mas} = 67\text{ mJy beam}^{-1}$ polarized flux density) corrected for Faraday rotation overlaid on Stokes $I$ contours. Contours start at 2.1 mJy beam$^{-1}$ and increase by factors of 2.
Fig. 28.—Spectral index $\alpha_{12.1}^{8.4}$ plot for 1749+096 overlaid on Stokes $I$ contours at 15 GHz. Contours start at 2.1 mJy beam$^{-1}$ and increase by factors of 2.
**Fig. 29.**—*Left:* RM image (*color*) for 2021+317 overlaid on Stokes I contours at 15 GHz. The inset is a plot of EVPA $\chi$ (degrees) vs. $j^2$ (cm$^2$). *Right:* Electric vectors (1 mas = 12.5 mJy beam$^{-1}$ polarized flux density) corrected for Faraday rotation overlaid on Stokes I contours. Contours start at 1.2 mJy beam$^{-1}$ and increase by factors of 2.

**Fig. 30.**—Spectral index $\alpha_{12.1}^{8.4}$ plot for 2021+317 overlaid on Stokes I contours at 15 GHz. Contours start at 1.2 mJy beam$^{-1}$ and increase by factors of 2.
Fig. 31.—Left: RM image (color) for 2201+315 overlaid on Stokes I contours at 15 GHz. The inset is a plot of EVPA $\chi$ (degrees) vs. $\lambda^2$ (cm$^2$). Right: Electric vectors (1 mas = 10 mJy beam$^{-1}$ polarized flux density) corrected for Faraday rotation overlaid on Stokes I contours. Contours start at 1.2 mJy beam$^{-1}$ and increase by factors of 2.

Fig. 32.—Spectral index $\alpha_{1.2}$ plot for 2201+315 overlaid on Stokes I contours at 15 GHz. Contours start at 1.2 mJy beam$^{-1}$ and increase by factors of 2.
Fig. 33.—Left: RM image (color) for 3C 446 overlaid on Stokes I contours at 15 GHz. The inset is a plot of EVPA $\chi$ (degrees) vs. $\lambda^2$ (cm$^2$). Right: Electric vectors (1 mas = 200 mJy beam$^{-1}$ polarized flux density) corrected for Faraday rotation overlaid on Stokes I contours. Contours start at 5.1 mJy beam$^{-1}$ and increase by factors of 2.

Fig. 34.—Spectral index $\alpha^{12}_{15}$ plot for 3C 446 overlaid on Stokes I contours at 15 GHz. Contours start at 5.1 mJy beam$^{-1}$ and increase by factors of 2.
The broad emission line region (BLR) is not a likely candidate for the foreground Faraday screen. The BLR is thought to be less than a parsec, with a small (1%) volume filling factor $e$ (Osterbrock 1989), and cannot account for Faraday effects that appear on scales of tens of parsecs. Reverberation mapping in AGNs provides similar size constraints for the BLR (Kaspi et al. 2000). In addition, the multiepoch RM maps of 3C 279 can be used to rule out the BLR as a source of variations in the core RM of this blazar. Koratkar et al. (1998) have shown that the Ly$\alpha$ line in 3C 279 does not track variations in the optical continuum over an 8 year period. This implies that as the optical continuum varies, any Faraday depth due to the BLR clouds would remain constant. Although the sampling interval of Koratkar et al. (1998) did not coincide with our RM monitoring, it seems reasonable to accept this finding and disregard the BLR as a Faraday screen candidate.

Proceeding out from the center of an AGN, the next viable candidate for the Faraday screen is the narrow emission line region (NLR), or the thermal gas expected to confine the NLR clouds. In Zavala & Taylor (2002, 2003) we ruled out the NLR clouds as a Faraday screen based on volume filling factor arguments similar to those used to eliminate the BLR clouds. If the NLR clouds are confined in the vicinity of the jet, this eliminates the volume filling factor argument.
The hot rarefied gas that confines the NLR clouds is ruled out, as the observed RM distributions in individual sources do not exhibit a zero-mean Gaussian distribution (Zavala & Taylor 2003). Even with this in mind, we examined the possibility of such a stochastic screen using the results of Melrose & MacQuart (1998). Melrose & MacQuart predict that the variance of the Stokes parameters $Q$ and $U$ should decrease as $\exp \left( - \frac{\lambda^4}{C_0 k} \right)$ in the presence of a stochastic foreground Faraday screen, while the expectation value $\langle Q^2 + U^2 \rangle$ should remain constant. This decrease in $Q$ and $U$ while $\langle Q^2 + U^2 \rangle$ remains constant is termed the “polarization covariance” by Melrose & MacQuart. We examined polarization covariance for the quasar 1611+343, whose RM distribution appears in Zavala & Taylor (2003). The spatial sampling of the RM distribution for this quasar was fairly good, and we found that the variance in $Q$ and $U$ increased with wavelength. The polarization covariance

![Graph showing core fractional polarization at 15 GHz vs. observed RM](image1)

**Fig. 37.**—Left: Core fractional polarization in percent at 15 GHz for the objects in Table 4 vs. observed RM. The filled circles show quasars, the open circles show two epochs of 3C 273, the open diamonds show five epochs of 3C 279, the crosses show BL Lac objects, and the open triangle shows the radio galaxy 3C 120. Right: Core fractional polarization in percent at 8 GHz for the objects in Table 4 vs. observed RM. The symbols are the same as in the left panel. The solid line represents the expected beam depolarization from a gradient in a foreground Faraday screen using eq. (3).

![Five-year curves of the core RM and fractional polarization](image2)

**Fig. 38.**—Five-year curves of the core RM and fractional polarization for the quasar 3C 279. The solid line shows the RM vs. epoch, the dashed line the 15 GHz core fractional polarization (%), and the 8 GHz core fractional polarization (%) is shown by the dash-dotted line. Error bars for the fractional polarization estimates are approximately the size of the plotted filled circles. Errors in the RM are only known for the three most recent epochs.
remained constant, or possibly increased slightly. This is further evidence against a purely random Faraday screen.

The accumulating RM observations reinforce the conclusion of Udornprasert et al. (1997) that the Faraday screen cannot be located in the interstellar or intergalactic medium, and we do not consider this suggestion further.

Essentially by process of elimination, we are left to consider a Faraday screen in close proximity to the relativistic jets of AGNs. This has important implications for probing the jet physics. An exciting example is the suggestion by Blandford (1993) that observers search for evidence of helical magnetic fields through observations of a gradient in the RM transverse to a jet axis. Asada et al. (2002) report the detection of an RM gradient across the jet of 3C 273 and interpret this as evidence for the helical magnetic field expected by some theories and simulations.

Interactions between the jets and ambient material in the centers of AGNs as described by Bicknell et al. (2003) have also been considered (Zavala & Taylor 2003). The mixing layer described in Zavala & Taylor (2002, 2003) also has potential as a foreground Faraday screen. Examinations of the relatively rare (Pollack et al. 2003) broad and polarized jets in AGNs will be required to settle the identity of the Faraday screen. For example, the interaction model can be tested by observing the alignment of magnetic vectors at the interaction site through shocks and the increasing fractional polarization due to this alignment relative to regions of the jet upstream from the supposed interaction.

If the Faraday screen is a turbulent mixing layer, then the upper limit to the layer thickness is approximately a jet radius. This requirement exists to prevent significant deceleration of the jet due to mass entrainment (DeYoung 2002; Rosen et al. 1999). Relativistic motion in the jets of quasars, BL Lac objects, and 3C 120 (Gómez et al. 2000) clearly shows that deceleration has not occurred. Nondetection of counterjets shows that relativistic beaming is still substantial and is another indicator that no significant deceleration has taken place. The deceleration argument limits the maximum screen thickness to less than the observed jet radius. The line-of-sight distance $L$ is constrained to about 10 pc or less.

In Zavala & Taylor (2003) an upper limit to $n_e$ was set at a few times $10^3$ cm$^{-3}$ because of the lack of apparent free-free absorption. Recently published electron densities for the narrow-line radio galaxy Cygnus A put $n_e$ at 300 cm$^{-3}$ (Taylor et al. 2003), and we consider this a useful lower limit. Thus, it is reasonable to set $n_e \approx 1000$ cm$^{-3}$. With typical jet RMs of 100–500 rad m$^{-2}$, the net line-of-sight $B$-field is $\sim 0.1–0.6 \mu G$ for a 1 pc path length. Should the same path lengths and electron densities be responsible for the core RMs of quasars, then the field strengths would be approximately $1–4 \mu G$, for RMs of 1000–3000 rad m$^{-2}$. However, the assumption of similar physical conditions for the screen within 10 pc of the black hole seems unlikely. A gradient in the physical conditions is expected as we proceed closer to the center of activity.

These magnetic fields are surprisingly weak. To be in equilibrium with a thermal gas similar to that in the NLR ($T = 10,000$ K, $n_e = 1000$ cm$^{-3}$) would require fields of approximately 200 $\mu G$, approximately 2 or more orders of magnitude larger than the simple estimates here produced for the $B$-fields. These weak field estimates may present a problem for a dynamically significant helical magnetic field. It is difficult to see how a helical field could be dynamically important for a relativistic jet with field strengths of less than 10 $\mu G$.

### 4.4. RM Properties and Optical Classification

For some time it has been apparent that optical AGN classification correlates with fractional polarizations. For example, Gabuzda et al. (1992) presented results that showed that the cores of BL Lac objects were more strongly polarized than quasar cores. This result was verified for a larger sample of AGNs by Pollack et al. (2003). Using arcssecond-scale polarization data, Saikia (1999) noted that BL Lac objects and core-dominant quasars had higher fractional polarizations than either lobe-dominant quasars or radio galaxies. Saikia attributed this to an orientation effect due to an obscuring torus that depolarizes the cores of radio galaxies and lobe-dominant quasars. Based on the high RMs found on parsecs scales in quasars, Taylor (2000) predicted lower core RMs in BL Lac objects as compared to quasars. This would arise if BL Lac objects had their jets more closely aligned to the line of sight and if the relativistic jets cleared out the magnetoionic gas responsible for the Faraday rotation. Contrary to this expectation, BL Lac itself was found to have a nonnegligible Faraday rotation (Reynolds et al. 2001). With this in mind, we examine whether the RM properties of the cores and jets of BL Lac objects and quasars are significantly different. Using the values for the peak rest-frame RMs (Table 4, col. [16]), we see that quasars and BL Lac objects appear to be different. Table 5 shows the number, the mean $\mu$, the error of the mean, and the median rest-frame RMs for quasars and BL Lac objects. For the quasars there are 26 measurements for 21 quasars because of the multiploch observations of 3C 273 and 3C 279. As only one radio galaxy has a core RM, we exclude this class from consideration. The quasars have a mean rest-frame RM $3 \times 10^{-2}$ times that observed for the BL Lac objects. The median values, which are less affected by outliers, agree with this result. As expected by Taylor (2000), BL Lac objects seem to have a systematically lower core RM compared to quasars. These are small-number statistics, and a Kolmogorov-Smirnov test (Press et al. 1992) gives a probability of 0.011 that the BL Lac object and quasar core RMs are drawn from the same parent distribution. This is only a 2.5 $\sigma$ result. Figure 39 is a histogram of the rest-frame core RM of BL Lac objects (hatched histogram) and quasars (open histogram). Clearly, small-number statistics limit our ability to distinguish any difference between the two AGN classes that might exist based on RM. All we can say is that there is a suggestion that quasar and BL Lac object core RMs are different, and better statistics are needed to establish this on a firm foundation.

Some shaking to this foundation has already occurred. Mutel & Denn (2004) report in their multiploch monitoring of BL Lac an observation of an RM of 6000 rad m$^{-2}$. This quasar-like RM further blurs the distinction between quasars and BL Lac objects that also exists in their optical spectral-line properties (Vermeulen et al. 1995). The BL Lac object redshift distribution does not extend much beyond a redshift of 1 (Rector & Stocke 2001), so we have only a small overlap for quasars and BL Lac objects with redshifts less than 1. Our primarily
single-epoch RM observations may certainly undersample a highly variable phenomenon, as Mutel & Denn (2004) and Zavala & Taylor (2001) demonstrate.

The same cannot be said for the jets of BL Lac objects and quasars. We used the 8–12 GHz spectral index maps to define the jets as the regions that are optically thin ($\alpha < -0.5$). The RM maps are blanked, retaining pixels where this criteria for $\alpha$ is met, which enables the RM distribution for the predominantly optically thin jet regions to be determined. We further required that these “jet” regions be at least 1 beamwidth from the map peak, the location where the core RM in Table 4 is taken. These criteria limited the number of sources for which we could investigate the jet RM statistics. Table 6 presents the results of this comparison, and the smaller number statistics are immediately apparent. Neither the mean nor the median values appear significantly different. A Kolmogorov-Smirnov test was not performed because of the small numbers present in this comparison. These small-number statistics, especially in the case of the BL Lac objects, and the already noted RM variability of BL Lac objects (§ 4.1) leave these comparisons of core and jet RM properties suspect. A larger sample of RM observations, with good time sampling, is required to confirm that the jet regions are indeed similar, while the cores appear different.

### 4.5. Breaking the $\chi^2$ Faraday Law

As noted in § 3 the $\chi^2$ law does not seem to be universally applicable. Both 0202+149 and 0420–014 are depolarized, perhaps through a superposition of components smaller than the beam size, and no fits to a $\chi^2$ law are possible. There are sources for which sufficient polarized flux is detected at all frequencies and a $\chi^2$ law does not seem applicable. Table 7 lists the sources for which agreement with a $\chi^2$ law seems unlikely based on the reduced $\chi^2$ obtained for the RM fits. Lack of agreement with the Faraday rotation law may result for several reasons, which we now consider.

Almost all sources have cores optically thick to synchrotron emission, as shown in the spectral index maps. This is especially true at 8 and 12 GHz. Observations at different frequencies see different $\tau = 1$ surfaces that may not have the same intrinsic polarization angle. If this were the case, the RM fits in the optically thick cores should always fail to agree with the $\chi^2$ law, as the $\lambda = 0$ position angles would not agree. This is not true in general, as most sources show good agreement with the $\chi^2$ law, even in the optically thick cores. This is especially true for 3C 273 and 3C 279, which show good agreement with the Faraday rotation law in their optically thick cores over several epochs, separated by timescales of months to a year. This is an interesting result, as it requires the different $\tau = 1$ surfaces to maintain the same polarization angle orientation. It is known that the jets collimate within a small distance from the black hole (Junor et al. 1999), and this collimation may also order the magnetic field within this short distance. For the optically thick regions of the jet, higher frequencies see farther down the jet and closer to the black hole (Blandford & Königl 1979). As the $\chi^2$ law holds in the optically thick regions, then the different $\tau = 1$ surfaces, located at different radii from the black hole, must have the same intrinsic polarization angle and hence magnetic field orientation.

There is no consistent observational picture for the sources that do not show good agreement with a $\chi^2$ law based on the reduced $\chi^2$ of the RM fits. Comparing Table 7 with Figure 36 shows that these sources are not systematically brighter or fainter relative to other sources in the sample. Optical class seems unimportant for the moment, as BL Lac objects and quasars appear in proportion to their representation in the sample as a whole. Opacity effects do not seem to be important, as optically thick sources do show good agreement with the Faraday law for most cases. We examined depolarization as a characteristic and found that the depolarization spans a wide range of values for these sources. Figure 40 shows the depolarization as the ratio of the 15 GHz fractional polarization to the 8 GHz fractional polarization. Arrows in Figure 40 show the locations of the five sources for which a reduced $\chi^2$ is not in agreement with that expected if the Faraday law were true. The most depolarized source in Figure 40 is 3C 273 (epoch 2000.07), which shows good agreement with a $\chi^2$ law, even with a high depolarization ratio. Homan et al. (2002) report that two sources (not included in this sample) also exhibit non-Faraday law behavior, based

| Source Type | Number | $\mu$ (rad m$^{-2}$) | $\sigma_{\mu}$ (rad m$^{-2}$) | Median (rad m$^{-2}$) |
|-------------|--------|----------------------|-------------------------------|----------------------|
| Quasars     | 12     | 600                  | 43                            | 458                  |
| BL Lac objects | 4     | 330                  | 20                            | 264                  |
on variations in polarization angles at two frequencies over several epochs.

5. CONCLUSIONS

The rotation measure properties for a sample of over 40 quasars, radio galaxies, and BL Lac objects are examined. The core RMIs in quasars are observed to vary from approximately 500 to several thousand rad m$^{-2}$ within 10 pc of the core. Jet RMIs are typically 500 rad m$^{-2}$ or less. The cores of the seven BL Lac objects examined have RMIs in their cores and jets similar to those of quasar jets. Radio galaxies usually have depolarized cores and exhibit RMIs in their jets varying from a few hundred to 10,000 rad m$^{-2}$. A gradient in the foreground Faraday screen is invoked to explain the observed depolarization properties of the sample. The Faraday screen is likely located close to the relativistic jet, although its exact nature remains unclear. Observations of broad, polarized jets are required to further constrain the identity of the Faraday screen. Net line-of-sight magnetic fields of 0.1–0.6 $\mu$G can account for the observed jet RMIs. If similar physical conditions exist in quasar cores, then the field strength required is of order 1 $\mu$G. Agreement with the $\chi^2$ law in the optically thick cores of quasars and BL Lac objects requires a constant magnetic field orientation at different $\tau = 1$ surfaces and thus at different radii from the black hole.

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