PROBING THE PARSEC-SCALE ACCRETION FLOW OF 3C 84 WITH MILLIMETER POLARIMETRY

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ABSTRACT

We report the discovery of Faraday rotation toward radio source 3C 84, the active galactic nucleus in NGC 1275 at the core of the Perseus Cluster. The rotation measure (RM), determined from polarization observations at wavelengths of 1.3 and 0.9 mm, is \((8.7 \pm 2.3) \times 10^5 \text{ rad m}^{-2}\), among the largest ever measured. The RM remained relatively constant over a 2 year period even as the intrinsic polarization position angle wrapped through a span of 300 degrees. The Faraday rotation is likely to originate either in the boundary layer of the radio jet from the nucleus, or in the accretion flow onto the central black hole. The accretion flow probably is disk-like rather than spherical on scales of less than a parsec, otherwise the RM would be even larger.

Subject headings: accretion, accretion disks — polarization — galaxies: active — galaxies: jets — galaxies: individual (3C 84)

1. INTRODUCTION

Radio source 3C 84 is associated with the active galactic nucleus (AGN) in NGC 1275, the central galaxy in the Perseus cluster, the prototypical ‘cooling flow’ cluster (Fabian 1994). The black hole in the AGN launches powerful jets into the surrounding medium. The accretion process onto the black hole has been studied through a variety of techniques on scales as small as a few parsecs (Vermeulen et al. 1994; Walker et al. 1994, 2000; Wilman et al. 2005; Scharwachter et al. 2013). At the distance of NGC 1275, 1 pc subtends 3 milliarcseconds.

At cm wavelengths 3C 84 is well-known as an ‘unpolarized’ calibrator. Why is this so, given that the radio emission from the AGN and its associated jet arise from synchrotron emission, which should be highly polarized? One possibility is that Faraday rotation twists the position angle \(\chi\) of this linearly polarized radiation as it propagates through foreground plasma. The position angle is rotated by \(\Delta \chi = \text{RM} \lambda^2\), where RM is the rotation measure. If RM varies across the source and the observations do not resolve this structure (“beam depolarization”), the net observed polarization may be very small.

Measurements of Faraday rotation along the line of sight to the black hole provide a valuable diagnostic of the accretion flow onto the central object, since the RM is proportional to the integral of the electron density and the magnetic field along the line of sight. In the case of SgrA*, for example, the RM has been used to constrain both the mode and the rate of the accretion onto its black hole (Bower et al. 2003; Marrone et al. 2007). Similar methods have recently been applied to M87 (Kuo et al. 2014). Time variability of the RM could also be a valuable probe of turbulence in the accretion region (Pang et al. 2011).

For 3C 84, Taylor et al. (2006) found an RM of about 7000 rad m\(^{-2}\) toward a small spot in the jet about 15 milliarcseconds (~ 5 pc) south of the nucleus, based on VLBA maps at wavelengths of 1.3, 2.0, and 3.6 cm. It was not possible to fit the RM toward the nucleus itself because in that direction linear polarization was detected only at a single wavelength (and only at the 0.2% level). At 7 mm, where emission from the nucleus becomes dominant, VLBA monitoring observations by the University of Arizona group (Pang et al. 2011) sometimes detect spots of weak linear polarization toward the nucleus, but typically the polarized flux density is < 0.5% of the peak flux density.

Polarization should be easier to detect at mm wavelengths because Faraday rotation decreases steeply at shorter wavelengths, and because the mm emission region is smaller, so that variations in RM across the source are less problematic. However, based on observations made with the Plateau de Bure interferometer in 2011 Mar, Trippe et al. (2012) placed upper limits of 0.5% on the linear polarization of 3C 84 at wavelengths of 1.3 and 0.9 mm. Here we report observations at the same wavelengths made over a 2 year period with the Combined Array for Research in Millimeter Astronomy (CARMA) and with the Submillimeter Array (SMA). The fractional polarization of 3C 84 was < 0.6% in the earliest data, from 2011 May, consistent with the Trippe et al. (2012) results, but by late 2011 it had increased to the 1–2% level. The RM inferred from the data is \(\sim 9 \times 10^5 \text{ rad m}^{-2}\), among the largest ever measured. We discuss the implications of these results for the accretion flow onto the black hole in 3C 84.

http://www.bu.edu/blazars/VLBAproject.html
2. OBSERVATIONS

2.1. CARMA Observations

The CARMA polarization system [Hull et al. 2013 2014] consists of dual-polarization 1.3 mm receivers that are sensitive to right- (R) and left-circular (L) polarization, and a spectral-line correlator that measures all four cross-correlations (RR, LL, LR, RL) on each of the 105 baselines connecting the 15 antennas.

The double sideband receivers are sensitive to signals at sky frequencies \( \nu_{\text{sky}} = \nu_{\text{LO}} \pm \nu_{\text{IF}} \) above (upper sideband) and below (lower sideband) the local oscillator frequency \( \nu_{\text{LO}} \). Signals received in these two sidebands are separated in cross-correlation spectra. The correlator provides 4 independently tunable sections, each up to 500 MHz wide. Typically we centered these sections (2013 May through 2013 August). In an 8-hour observation on 2013 August 04. Symbols indicate the LO frequency used for the observations – circles, 218 GHz; crosses, 232.5 GHz; triangles, 247 GHz. The sky frequencies observed at \( \nu_{\text{LO}} \) of 232.5 GHz overlap those observed at 218 and 247 GHz. The error bars are estimated from the scatter in the measurements at each frequency and do not fully reflect systematic errors in the polarization leakage calibration. Fractional polarizations of 1.5% were measured for both 3C 84 and 0359+509; 0359+509 has a much lower flux density than 3C 84, so the position angle uncertainties due to thermal noise are larger. Rotation measures are derived from fits to the position angle vs. frequency, indicated by the blue curves.

IF. The available observational bandwidths were either 2 GHz or 4 GHz. Thus the data spanned a sky frequency range of either 10 GHz or 12 GHz.

Data were reduced using a combination of the MIR/IDL and MIRIAD data reduction packages. The instrumental polarization is frequency-dependent and the typical values are ~ 2%. The instrumental polarization is determined with an accuracy of ~ 0.1%. The RM was fit to the difference in the upper and lower sideband position angles.

3. RESULTS

The 3C 84 data reported here span the period from 2011 May through 2013 August. In almost all cases 3C 84 was observed as a calibrator for another science target. Many of the CARMA datasets were from the TADP POL survey [Hull et al. 2014].

One CARMA observation targeted 3C 84 specifically. In an 8-hour observation on 2013 August 04 we interleaved observations at LO frequencies of 218, 232.5, and 247 GHz to obtain wide parallactic angle coverage at 16 sky frequencies from 210–255 GHz. Both 3C 84 and a comparison calibrator, 0359+509, were observed. Fits to these data, shown in Figure 2, give RM of \((7 \pm 5) \times 10^3 \text{ rad m}^{-2}\) for 3C 84 and \((1.9 \pm 7.6) \times 10^3 \text{ rad m}^{-2}\) for 0359+509. The uncertainty is large for 0359+509 because this source is at
ative values, apparently wrapping through from position angle trended monotonically toward more negative observations as it was in the 1–2% range. The polarization was very low, data, from 2011 May, the fractional polarization of 3C 84 summarized in Table 1 and plotted in Figure 2. In our earliest could be an instrumental effect.

The fractional polarizations, position angles, and rotation measures observed at 1.3 mm (blue squares, CARMA; red circles, SMA) and 0.9 mm (green triangles, SMA) from 2011 Aug through 2013 Dec. Optical fractional polarizations and position angles measured at Lowell Observatory are shown by black crosses. The dashed lines in the middle panel show that in mid-2012 the position angles at 0.9 mm were roughly $35^\circ$ more negative than those at 1.3 mm, consistent with a rotation measure of $6 \times 10^5$ rad m$^{-2}$. Dashed lines in the top panel show the mean $\pm 1$ standard deviation of the 1.3 mm RM measurements.

redshift $z=1.52$, and the RM scales as $(1+z)^2$; however, the 0359+509 data rule out the possibility that the systematic $25^\circ$ position angle variation measured for 3C 84 could be an instrumental effect.

The fractional polarizations, position angles, and rotation measures derived from all observations are summarized in Table 1 and plotted in Figure 2. In our earliest data, from 2011 May, the fractional polarization of 3C 84 was very low, $\lesssim 0.6\%$, but for most of the following observations it was in the 1–2% range. The polarization position angle trended monotonically toward more negative values, apparently wrapping through from $-90^\circ$ to $+90^\circ$ twice the 2 year span of the observations.

Also plotted in Figure 2 are the R-band optical polarizations and position angles for 3C 84 measured with the 1.8-m Perkins telescope at Lowell Observatory (Flagstaff, AZ) using the PRISM camera. The observations and data reduction were performed in the same manner as described by [Jorstad et al., 2010] for the quasar 3C454.3. The 1–2% fractional polarization in the optical is similar to that at mm wavelengths, but there is not a simple correspondence between the optical and mm position angles; $\chi_{\text{opt}}$ sometimes fluctuates by tens of degrees on time scales of days, while $\chi_{\text{mm}}$ tends to vary more smoothly.

Generally there is good agreement between the CARMA and SMA results at 1.3 mm; significant RM measurements were made with both instruments. It was not possible to detect Faraday rotation from the 0.9 mm data alone – at this wavelength the expected position angle difference between the upper and lower sidebands is only $2.5^\circ$ for an RM of $10^5$ rad m$^{-2}$. However, interpolation of the data in Figure 2 shows that position angles at 0.9 mm were $30–40^\circ$ more negative than those at 1.3 mm in mid-2012. The fact that this offset is maintained over a period of months even as the position angles at both wavelengths rotate through 90 degrees provides powerful evidence that we are observing Faraday rotation in an external screen, rather than variations in the polarization direction vs. synchrotron optical depth. A $35^\circ \pm 5^\circ$ difference in the 1.3 mm and 0.9 mm position angles corresponds to an RM of $(6 \pm 1) \times 10^5$ rad m$^{-2}$.

The uncertainties in the RM measurements listed in Table 1 do not fully account for possible systematic errors in the polarization leakage corrections. Thus, although our results allow for possibility of up to 50% variations in the RM on time scales of days or weeks, the evidence for such variations is not convincing. An average of the 1.3 mm RM values, excluding the anomalous result from 2011 May, gives $\text{RM} = (8.7 \pm 2.3) \times 10^5$ rad m$^{-2}$, where the uncertainty is the standard deviation of the measurements.
4. INTERPRETATION

Where do the linearly polarized emission and Faraday rotation originate in 3C 84, and what conclusions can we draw about the source?

4.1. Source of the polarized emission

We expect that at wavelengths of $\lesssim 1.3$ mm most of the flux originates from a small region, probably less than a milliarsecond ($\lesssim 0.4$ pc) across, centered close to the nucleus. For an AGN with radio jets the mm emission “core” is thought to be located somewhere in the approaching jet, displaced from the black hole.

In blazars, where the jet is closely aligned with our line of sight, the core may be offset by thousands of Schwarzschild radii ($R_S$) from the black hole, near the end of the zone where the jet is electromagnetically accelerated, because this is where Doppler boosting is greatest. For jets that are viewed at a substantial angle, however, this model predicts that the core should be close to the base of the jet (Marscher 2006). In M87, for example, where the jet is inclined by $\sim 20^\circ$ with respect to the line of sight, VLBA observations by Hada et al. (2011) show that the 7 mm radio core is offset by only 14–23 $R_S$ from the black hole, while 1.3 mm VLBI observations appear to resolve the base of the jet, just 2.5–4 $R_S$ from the black hole (Doeleman et al. 2012). The jets in 3C 84 are mildly relativistic (0.3–0.5c) and are directed at an angle of roughly $30^\circ$ to $55^\circ$ to the line of sight (Walker et al. 1994, Asada et al. 2000), so here too the offset of the core from the black hole may be small.

Variations in the polarization position angle presumably are caused by changes in the magnetic field structure of the emitting region, possibly as the result of shocks propagating along the jet similar to what is seen in blazars (e.g., Aller et al. 1999). Optical emission originates in these same shocks, although from volumes that are much smaller, leading to faster fluctuations in the optical position angles (Jorstad et al. 2010). The rotation of 3C 84’s optical and mm polarization position angles with time is reminiscent of the systematic variations seen in BL Lac in late 2005. In BL Lac, this rotation was correlated with an optical, X-ray, and radio outburst, and was attributed to a shock propagating along a helical magnetic field in the jet (Marscher et al. 2008).

4.2. Location of the Faraday screen

Where, then, is the Faraday screen? Is it close to the nucleus, or far away in the intrachuster gas? The rotation measure is given by (Gardner & Whiteoak 1966)

$$RM = 8.1 \times 10^5 \int n_e B \cdot dl \text{ radians m}^{-2},$$

where $n_e$ is the thermal electron density in cm$^{-3}$, $B$ is the magnetic field in gauss, and $dl$ is the path length along the direction of propagation in pc. Only the component of the magnetic field along the line of sight contributes; if the field is tangled, with many reversals along the line of sight, the RM will be reduced.

It is implausible that the Faraday rotation originates in the intrachuster gas. Typical RMs toward cooling flow clusters are in the range $10^3$ to $10^4$ rad m$^{-2}$ (Carilli & Taylor 2002), similar to the RM of 7000 rad m$^{-2}$ measured by Taylor et al. (2006) 15 mas (5 pc) from 3C 84’s nucleus. The RM could be higher if we happen to view the nucleus along the axis of one of the partially ionized filaments that thread the intrachuster gas surrounding NGC1275 (Conselice et al. 2001). These filaments, 10–100 pc in diameter and several kpc long, are stabilized by $10^{-3}$ gauss magnetic fields (Fabian et al. 2008). If our line of sight to the nucleus passed precisely along the axis of such a filament it could account for the measured RM, but such perfect alignment is improbable.

Probably the Faraday screen is close to the nucleus, within a parsec of the emission core. We cannot be certain whether the material in this screen is being blown out from the black hole or is accreting onto it. We consider these two possibilities below.

4.3. Faraday rotation in the jet boundary layer?

Faraday rotation might originate in the sheath or boundary layer of the radio jet, in plasma that is flowing outward from the black hole. Zavala & Taylor (2004) suggested such a geometry to explain the Faraday rotation measured in a sample of 40 radio galaxies and quasars observed with the VLBA at wavelengths of 2 cm to 3.6 cm. Rotation measures were typically $10^3$ to $10^4$ rad m$^{-2}$ for the radio cores in these sources. This is comparable to the RM of about 7000 rad m$^{-2}$ measured in the 3C 84 jet 5 pc from the nucleus by Taylor et al. (2006) at wavelengths of 1.3 to 3.6 cm. The much higher RM that we measure at 1.3 mm might be explained if the mm emission originates closer to the base of the jet and thus propagates through a denser zone of the boundary layer.

In fact, an increase of RM at shorter wavelengths appears to be common in radio jets. In an AGN polarization survey, Jorstad et al. (2007) found that the RM measured at mm wavelengths was greater than the RM measured at cm wavelengths in 8 of 8 sources; a fit to these data gave $|RM(\lambda)| = \lambda^{-a}$, with $a = 1.8 \pm 0.5$. This dependence can be explained by a simple model in which the $\tau \sim 1$ surface is located at distance $d \propto \lambda$ along the jet, and where the magnetic field, path length, and electron density in the boundary layer scale as $d^{-1}$, $d$, and $d^{-2}$ respectively, giving $|RM(\lambda)| \propto \lambda^{-a}$ (Jorstad et al. 2007).

For 3C 84, scaling the 1.3 cm RM of 7000 rad m$^{-2}$ by $\lambda^{-2}$ gives RM $\sim 7 \times 10^5$ rad m$^{-2}$ at 1.3 mm, in good agreement with the measured value. We caution that this agreement may be a fortuitous coincidence. The model assumes that the cm emission originates 10 times farther from the nucleus than does the mm emission. In fact, however, the mm emission likely originates within a few $\times 0.1$ mas of the nucleus, whereas the cm RM was measured at the tip of the jet 15 mas away, so the actual distance ratio is closer to 100.

4.4. Faraday rotation in the accretion flow?

We now consider the possibility that the Faraday rotation originates in the accretion flow onto the black hole. The RM, $\sim 9 \times 10^5$ rad m$^{-2}$, is among the largest ever detected. However, it is striking for the fact that it is not larger. It is less than a factor of two greater than the RM observed toward SgrA*, which is thought to originate in a radiatively inefficient accretion flow (RIAF) surrounding the black hole (Bower et al. 2003, Marrone et al. 2007). For SgrA* the RM constrains the accretion rate onto the...
Accretion flow models fall into two classes. RIAF models may not be valid for all sources, especially those near the transition between RIAF and thin-disk accretion.

9 Note that there is a typographical error in equation (9) of Marrone et al. (2006) — the power law index for $r_{in}$ should be $-3/4$ (Macquart et al. 2006).
4.5. Time variability

On timescales of decades the emission from 3C 84 varies dramatically, both in the radio and in the γ-ray band; currently the source is brightening rapidly (Dutson et al. 2014), suggesting increased fueling of the black hole. Figure 1 in Dutson et al. (2014) shows that the 1.3 mm flux density increased by a factor of about 1.6 from mid-2011 to mid-2013. Over this same time span our polarization measurements show no apparent systematic increase in the RM. This suggests that processes inside \( r_{in} \), control accretion onto the black hole, or that our line of sight to the mm core does not pass through the inner accretion flow. More precise measurements of the RM would be valuable to search for variability caused by turbulence or patchiness in the accretion flow, as in the SgrA* models of Pang et al. (2011). Or, if the polarized mm emission originates in a hot spot moving outward along the radio jet, then changes in the RM could be used to probe the structure of the accretion flow as a function of radius.

5. SUMMARY

Polarization observations with CARMA and the SMA show that radio source 3C 84 is linearly polarized at wavelengths of 1.3 mm and 0.9 mm. The variation in position angle with wavelength is consistent with Faraday rotation, with a rotation measure of \((8.7 \pm 2.3) \times 10^5 \text{ rad m}^{-2}\), among the largest ever measured. The fractional polarization was 1–2% over most of the 2 years spanned by these observations. The rotation measure was stable within ±50% over this period, even as the polarization position angle drifted steadily toward more negative values, wrapping through a span of roughly 300 degrees.

We argue that at mm wavelengths the linearly polarized radiation from 3C 84 originates from the nucleus of the system, possibly within tens of Schwarzschild radii of the black hole, and that the Faraday screen lies just in front of the emission region. It is uncertain whether the Faraday rotation originates in or on the boundary layer of the radio jet, or in the accretion flow onto the black hole. We investigated whether quasi-spherically radiatively inefficient accretion flow (RIAF) models could explain the measured RM but found that they overpredicted it by several orders of magnitude. This suggests that on scales of less than a parsec the accretion flow onto the black hole is primarily disk-like rather than spheroidal. The geometry of the disk previously inferred from free-free absorption appears to be correct, with the disk obscuring the counterjet and the innermost parts of the core.

More highly inclined systems such as Centaurus A may exhibit even larger RMs. Such sources would appear unpolarized in broadband observations. Spectropolarimetry at mm wavelengths with CARMA, SMA, and ALMA provides a powerful tool to uncover the accretion flows in these systems.

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