The Central kpc of Starbursts and AGN
ASP Conference Series, Vol. xxx, 2001
J. H. Knapen, J. E. Beckman, I. Shlosman, and T. J. Mahoney

Magnetic Fields in the central kiloparsec of Active Galactic Nuclei

G.B. Taylor

National Radio Astronomy Observatory, 1003 Lopezville Rd, Socorro NM 87801, USA

R.T. Zavala

Department of Astronomy, New Mexico State University, Dept. 4500, Box 30001, Las Cruces, NM 88003, USA

Abstract. Given the energetic nature of AGN, it is likely that magnetic fields exist in their central kiloparsecs. These magnetic fields are expected to play a vital role in the formation and collimation of the jets. We are just beginning to exploit milliarcsecond resolution Faraday Rotation Measure (RM) studies of the jets in radio galaxies, quasars and BL Lac objects. These studies, undertaken with the Very Long Baseline Array at frequencies of 8-43 GHz, provide information about the density weighted magnetic field along the line-of-sight, and can thus provide information on the strength and topology of the fields. Substantial RMs of up to 40,000 rad m^{-2} have been detected in the inner jets of quasars, declining sharply on scales of $\sim$100 pc. And as jet components move they sample new sightlines and show changes in their RM on timescales of months to years.

1. Introduction

Using the Very Long Baseline Array (VLBA) telescope it is possible to image the central kiloparsec of Active Galaxies, even at high redshift. Given a sufficiently bright and polarized radio source we can study the change in polarization angle as a function of frequency in order to determine the Faraday Rotation Measures (RMs). These RMs in turn tell us about the magnetic fields in the environment of AGN. This is illustrated in Fig. 1 which shows the VLA looking at a polarized source through a Faraday screen. To obtain the RM distribution one measures the polarization angle at three or more widely spaced frequencies and solves for the slope of the best fit to a λ^2-law on a pixel-by-pixel basis.

For an external Faraday screen the rotation measure is given by

$$RM = 812 \int_0^L n_{\rm e} B_{||} {\rm d}l \ \text{radians m}^{-2} \ , \tag{1}$$

where n_e is the electron density in cm^{-3}, $B_{||}$ is in mGauss, and l is in pc. On average the magnetic field, B, will be larger than the parallel component, $B_{||}$,

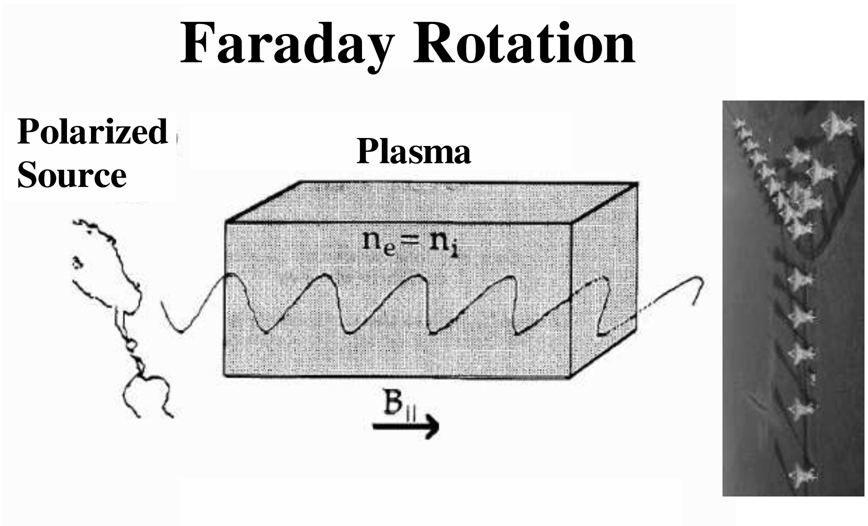

Figure 1. Schematic showing the effects of Faraday Rotation on radiation from a polarized source.

by $\sqrt{3}$. If the magnetic field is tangled, then it will be larger by a factor $N^{1/2}$ where N is the number of cells along the line-of-sight.

In the following sections we discuss what has been learned from recent observations of the RM distributions in the central kiloparsecs of AGN. We assume $H_0 = 50$ km s^{-1} Mpc^{-1} and q=0.5 throughout.

2. 3C 216

The quasar 3C 216 was found to have high RMs in the single dish surveys of Tabara & Inoue (1980) and in VLA observations made by Taylor, Ge & O'Dea (1995). Venturi & Taylor (1999) observed 3C 216 at high angular resolution with the VLBA and found Faraday rotation measures (RMs) in excess of 700 rad m^{-2} in the arc of emission located at $\sim$ 140 mas from the core (Fig. 2). Rotation measures in the range -300 – $+300$ rad m^{-2} are detected in the inner 5 mas ($\sim$ 30 parsecs). While the rotation measure near the core can be explained as due to a magnetic field in the narrow line region, they favor the interpretation for the high RM in the arc as due to a "local" Faraday screen produced in a shock where the jet is deflected by the interstellar medium of the host galaxy. These results indicate that a galactic magnetic field of the order of $\sim$ 50 μG on a scale $>$ 100 pc must be present in the ambient medium. A density of 0.1 cm^{-3} has been assumed based on studies of the ISM of low redshift galaxies (Fanti et al. 1995).

3. OQ 172

Until recently measurements of the magnetic field orientation in quasars (e.g. Cawthorne et al. 1993) have been assumed to have negligible Faraday Rota-

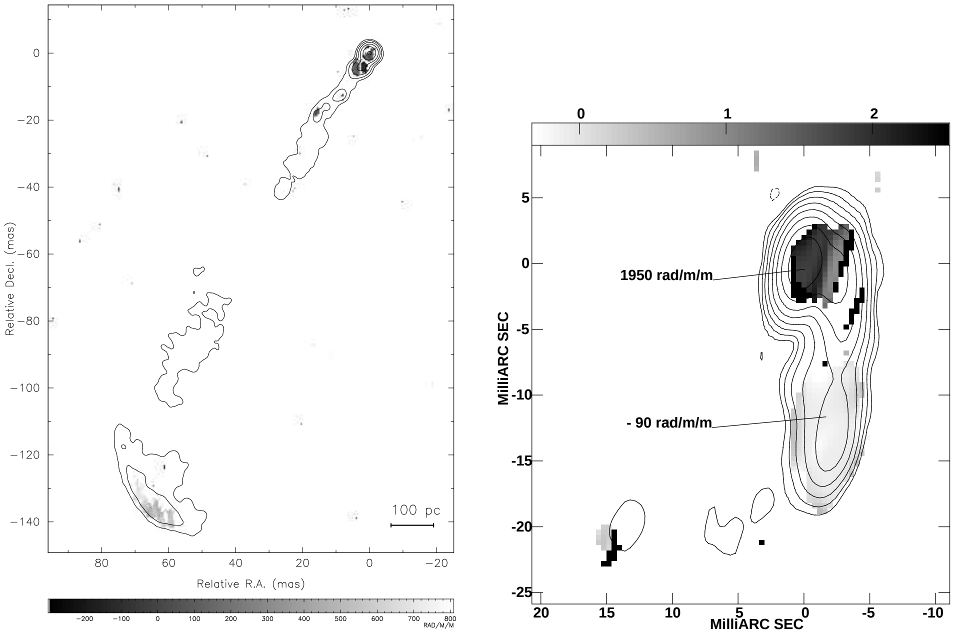

Figure 2. Rotation measure images of 3C 216 (*left*) and OQ 172 (*right*) with contours of 6 cm total intensity superposed.

tion, or to have a constant Rotation Measure (RM) equal to the integrated RM measured by the VLA or single dish telescopes. This situation arose from the difficulty (before the VLBA was built) in obtaining the simultaneous, multi-frequency VLBI polarimetry needed to determine the RM on the parsec-scale. Observations of OQ 172 by Udomprasert et al. (1997) were the first to reveal high RMs in the nuclear region (Fig. 2). After correcting for the source redshift (z=3.52), the observed RMs reach 20,000 rad m^{-2} in the rest frame of the source in the core and inner jets. Only 10 mas from the nucleus the jet |RM|s fall to less than 100 rad m^{-2} – low enough to be produced entirely by the passage of the radiation through the interstellar medium of our galaxy. Such differences in the RM structure on scales of 50 parsecs rule out a cluster magnetic field Faraday screen thought to be the dominant mechanism for producing the high RM objects seen at lower redshift.

4. A sampling of AGN

To further investigate the parsec-scale RM distribution in quasars we are performing multi-frequency polarimetric observations of a sample of 40 quasars, BL Lacs and radio galaxies using the VLBA. Some early results for 4 quasars (see Fig. 3) have been published in Taylor (1998), and the sample is defined in Taylor (2000). High RMs are found in the nucleus of almost every quasar within a projected distance of $\sim$ 20 pc from the core of the quasars. Beyond this distance the RMs decrease to $\leq$ 100 rad m^{-2}.

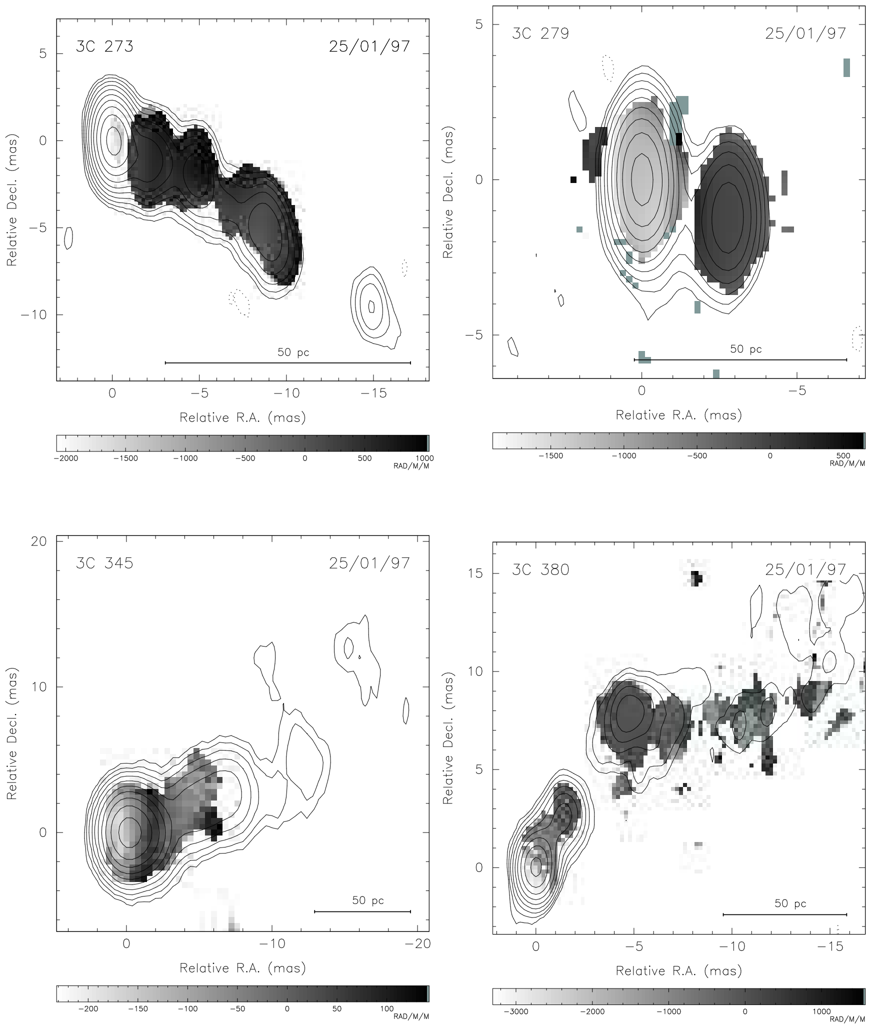

Figure 3. Rotation measure images of 3C 273, 3C 279, 3C 345, and 3C 380 with contours of total intensity superimposed.

Zavala & Taylor (2001) showed that both 3C 273 and 3C 279 show variations in their RM properties. The central region of 3C 279 changes from -1300 to > -500 rad m^{-2} between the 1997.07 and 1998.5 observations. 3C 279 maintains this lower RM during 2000.07 observations with the exception of a "bridge" of high RM which appears to connect the central region with component C4.

We find good agreement to a λ^2 law except near the core of 3C 273 and the resolved bridge of 3C 279. The high RMs observed in the central regions could result from the passage of the radiation through the narrow-line region (NLR) of the quasar. If the measured RM results from a polarized component which dominates within the telescope beam then the RM of the central region should vary as new components are created and ejected. As these new components emerge from the core their radiation passes through the NLR and a high RM results. The component progresses along the jet and the RM varies as the line of

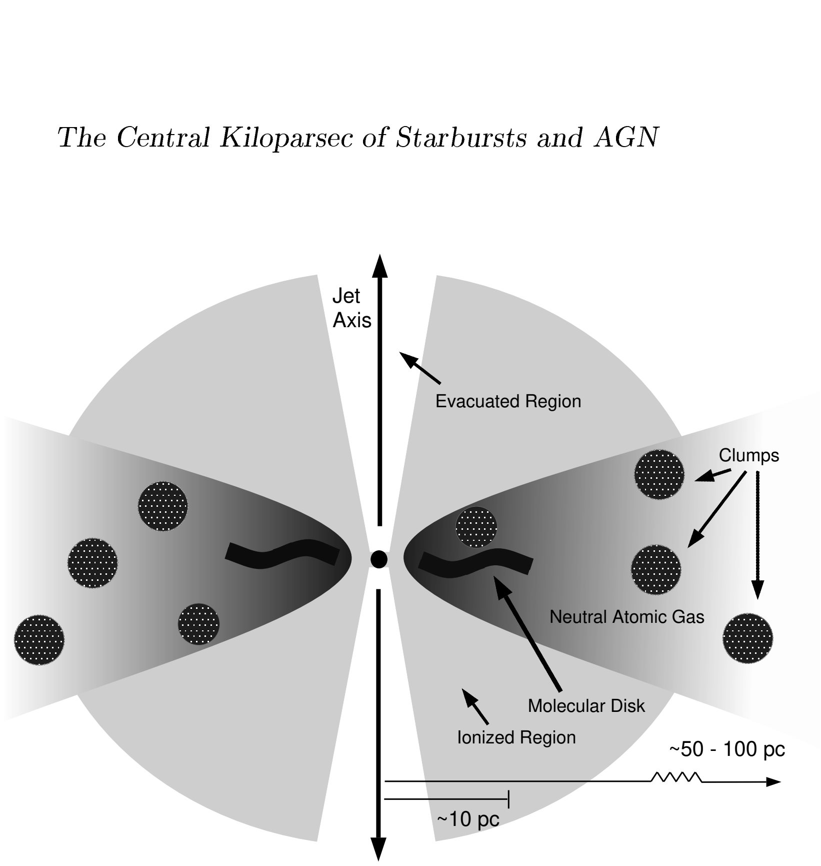

Figure 4. Cartoon model of the environment around an AGN.

sight traverses an inhomogeneous NLR Faraday screen. Eventually RMs below 100 rad m^{-2} should be observed, which are comparable to RMs produced by traversing the ISM of the galaxy, as the NLR is exited. With this picture the jet of 3C 273 may still probe the NLR as the RM in the jet of this quasar in the 8–15 GHz mosaic is approximately 5 times that observed in radio galaxy hosts (Feretti et al. 1999). We intend to monitor the cores of quasars for time variations in the RM created as new components are ejected and sample these regions.

Based on sub-mas resolution images of the RM distribution in 3C 273 and 3C 279, Zavala & Taylor (2001) found an approximate transverse scale size of 1 pc. A crude estimate of the magnetic field strengths in these quasars can be obtained assuming all the Faraday Rotation is produced in traversing a 1 pc long cell. The properties of the gas that produces the narrow-line region are not well established in these sources so for now we assume a typical electron density $n_e = 10^4$ cm^{-3} and volume filling factor $\epsilon = 1$. For a typical RM of 2000 rad m^{-2}, this gives a $n_e B$ product of $\sim$1 μG cm^{-3}. If the volume filling factor is more like 0.001 (Osterbrock 1989) then the field strengths could be larger by a factor of 1000. Also, larger field strengths will be required if the field is tangled along the line-of-sight.

5. A cartoon model and implifications for the Unified Scheme

In Fig. 4 a simple cartoon schematic for the AGN environment is shown. The details of the equatorial region are based on discussions in Peck, Taylor & Conway (1999). According to unified schemes, core-dominated quasars are viewed such that the jet axis makes only a small angle to the line-of-sight, and they therefore exhibit one-sided jets, apparent superluminal motions, and broad optical emission lines. While jet components are within $\sim$100 pc of the center of activity they are viewed through ionized gas which acts as a Faraday screen. Once the jet components move farther from the nuclear environment the RM rapidly drops.

For the Compact Symmetric Objects (CSOs) which can have a jet axis at large angles to the line-of-sight and often have intrinsic sizes less than $\sim$100 pc, all the components will be viewed through a dense multi-phase medium and extremely high RMs ($>>$ 50000 rad m^{-2}) are therefore to be expected if the model shown in Fig. 5 is correct. Unfortunately such extreme RMs will depolarize the radio source and hence cannot be measured directly. Recent VLBA polarimetry of 20 CSOs by Peck & Taylor (2000) place typical limits on the fractional polarization in CSOs of $<$1%. No polarized flux on the parsec-scale has ever been reported for a CSO.

Acknowledgments. The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation. R.T.Z. gratefully acknowledges support from the NRAO Summer Graduate Student Research Program and NSF Grant HRD-9628730.

References

Cawthorne, T. V., Wardle, J. F. C., Roberts, D. H., Gabuzda, D.C., & Brown, L. F. 1993, ApJ, 416, 496

Fanti, C., Fanti, R., Dallacasa, D., Schilizzi, R. T., Spencer, R. E. & Stanghellini, C. 1995, A&A, 302, 317

Feretti, L., Perley, R., Giovannini, G. & Andernach, H. 1999, A&A, 341, 29

Osterbrock, D.E. 1989, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei* (Mill Valley: University Science Books)

Peck, A. B., & Taylor, G. B. 2000, ApJ, 534, 90

Peck, A. B., Taylor, G. B., & Conway, J. E. 1999, ApJ, 521, 103

Tabara, H. & Inoue M., 1980, A&ASS, 39, 379

Taylor G. B., Ge, J. & O'Dea, C. P. 1995, AJ, 110, 522

Taylor, G. B. 1998, ApJ, 506, 637

Taylor, G. B. 2000, ApJ, 533, 95

Udomprasert, P. S., Taylor, G.B., Pearson, T.J., &

Roberts, D.H. 1997, ApJL, 483, L9

Venturi, T., & Taylor, G.B. 1999, AJ, 118, 1931

Zavala, R.T., & Taylor, G.B. 2001, ApJ, 550, L147