Spectropolarimetry of Radio Galaxies With Double-Peaked Emission Lines

Laura Kay[1,2]

Department of Physics and Astronomy, Barnard College, Columbia University, NY NY 10027

Michael Eracleous[1,3] & Edward C. Moran

Department of Astronomy, University of California, Berkeley CA 94720

A. M. Magalhães[1]

Instituto Astronomico e Geofisico, Universidade de São Paulo, Caixa Postal 9638, São Paulo, SP 01065-970, Brazil

Jules Halpern

Columbia Astrophysics Laboratory, 550 West 120th Street, New York, NY 10027

Abstract. We have conducted spectropolarimetry observations on five bright radio galaxies with structure, usually double peaks, in their broad Hα lines. Here we discuss primarily our observations of 3C 390.3, a well-known double-peaked emitter that is polarized. Much of its polarization may arise from Galactic interstellar polarization. Our other targets also do not show double-peaked Hα in the polarized flux that is predicted in simple models of accretion disk emission.

1. Introduction

A spectroscopic survey of the broad Hα emission lines of radio-loud AGNs by Eracleous & Halpern (1994) has shown that double-peaked emission lines occur in about 10% of these objects and has established their hosts as a reasonably homogeneous class. These exotic line profiles provide (potentially) the most direct dynamical evidence for the presence of accretion disks in AGNs (Chen & Halpern 1989, 1990), although alternative interpretations such as the bipolar outflow (twin jet) model (Zheng et al. 1990, 1991; Sulentic et al. 1995), and the binary black hole hypothesis (Gaskell 1983; Stockton & Farnham 1991; Gaskell

---

[1]Visiting Astronomer, Cerro Tololo Inter-American Observatory. CTIO is operated by AURA, Inc. under contract to the National Science Foundation.

[2]NSF International Research Fellow and NSF Career grantee

[3]Hubble Fellow

1996) are also possible but far less appealing (Eracleous 1988). The direction and magnitude of the polarization of the broad lines constitute independent probes of the geometry of the line-emitting region and can serve as tests of competing scenarios for the origin of the lines. In the accretion disk model, for example, the broad Balmer lines of these objects could be polarized about 1% for estimated average disk inclination angles. The polarized line profile can differ significantly from the total flux profile because of the effects of relativistic aberration on viewing angle over the surface of the disk; thus the relative heights of the two peaks in polarized flux can differ from that in the total flux.

2. Observations

The bright radio galaxies (3C 445, 3C 390.3, 3C 382, Pictor A, and PKS 0921–213) were selected because their Hα lines are stronger than that of a previously studied double-peaked galaxy Arp 102B (Antonucci et al. 1996). 3C 390.3 has been known for quite some time to display double-peaked emission lines characteristic of an accretion disk (Oke 1987, Pérez et al. 1988). 3C 382 was observed by Antonucci (1984), who found that the polarized line profile of Hα has a blue satellite with a position angle of polarization perpendicular to the radio axis, whereas that of the adjacent continuum is parallel to that axis. 3C 445 was selected as an optically bright object, although its Balmer line profiles do not display any double-peaked structure. Pictor A is a broad-line radio galaxy which has recently developed a strong double-peaked component to its Balmer emission lines (Halpern & Eracleous 1994; Sulentic et al. 1995). PKS 0921–213 is a new double-peaked source (Simpson 1994; Eracleous & Halpern 1998).

Our observations were conducted in August 1995 and July 1996 at the 3m Shane reflector at Lick Observatory with the red camera on the KAST spectrograph in spectropolarimetry mode, and at the CTIO 4m in January 1997 with a new spectropolarimeter (Kay et al. 1998a) on the RC Spectrograph. Data reduction and analysis were performed using the *VISTA* software package originally developed at Lick Observatory, and additional routines. Polarization standard stars and null stars were observed in order to check the instrumental polarization of the system and check for accuracy of the measurements. A nearby field star was measured for two of the galaxies as a check for interstellar polarization contamination. All averaging and summing of data sets was done in the Stokes parameters Q and U, and then new average values for polarization P, position angle θ, and polarized flux $P \times F$ were computed.

3. Results

3.1. 3C 390.3

3C 390.3 was observed at Lick for a total of 4 hours. The combined data for our observations of 3C 390.3 is shown in Fig. 1a. All flux spectra have been corrected for the atmospheric B band. Some structure in the Hα profile is seen in the polarized flux, but overall the polarized flux is very similar to the direct flux. The Galactic latitude is 27°, and the [OIII] lines appear in the polarized flux, suggesting that interstellar polarization might be a factor in these measurements.

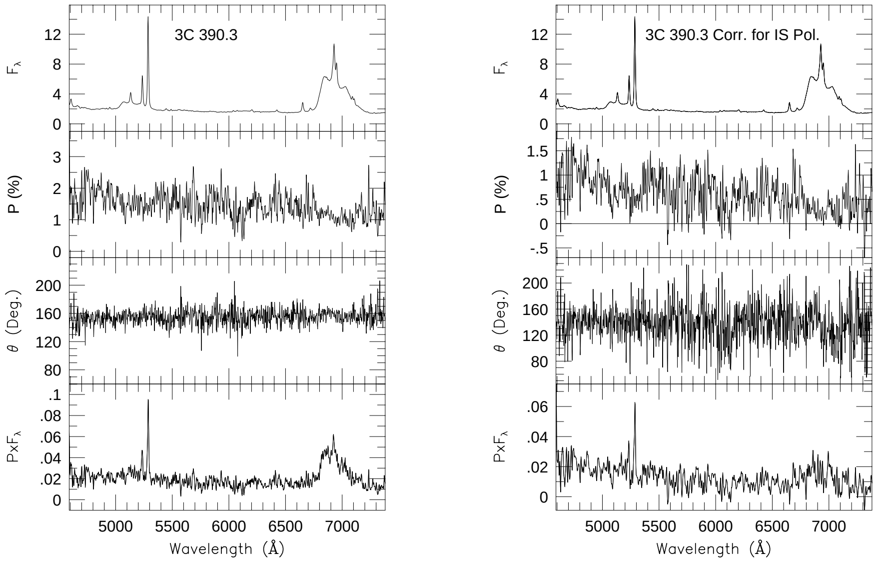

Figure 1. 3C 390.3, uncorrected (left), corrected (right)

Thus we observed 2 field stars nearby in the sky plane, 2–3′ from 3C 390.3, to see if the measured polarization originated from an interstellar Galactic screen.

The averaged measured Q and U values of the stars were used to create interstellar polarization curves, which were then subtracted from those of 3C 390.3. P and θ were recalculated and the corrected spectrum of 3C 390.3 is shown in Fig. 1b. The flux (but not P) was corrected for starlight, estimated to be 15%, and for Galactic reddening. This procedure removes most of the structure in the polarized flux, and reduces P from 1.3% to about 0.4%. A slight change in position angle may occur across Hα, but it is difficult to measure any change in P or $P \times F$ across the line.

This result is different from that of Corbett et al. (1998), who did not correct for interstellar polarization and fit models to the peaks in their polarized flux spectrum. Ideally we'd like to measure a few more nearby stars to be more certain of the interstellar correction, but 'El Niño' has prevented that so far.

3.2. Other Objects

Observations of the other targets are discussed in detail in Kay et al. (1998b). We observed 3C 382 for 8 hours at Lick. The data show that the continuum has a higher P than the lines, and P of Hα is considerably smaller (Fig. 2a). Some change of θ occurs across Hα, but not 90° as seen by Antonucci (1984). When P is corrected for the low interstellar polarization measured with a nearby field star, and the flux is corrected for a starlight fraction of 10% and for Galactic reddening, we see some structure in the polarized flux but it is still noisy. The continuum polarization does not vary strongly with wavelength and may be indicative of electron scattering. The continuum position angle of polarization is within 10 degrees of the radio position angle seen by Antonucci (1984).

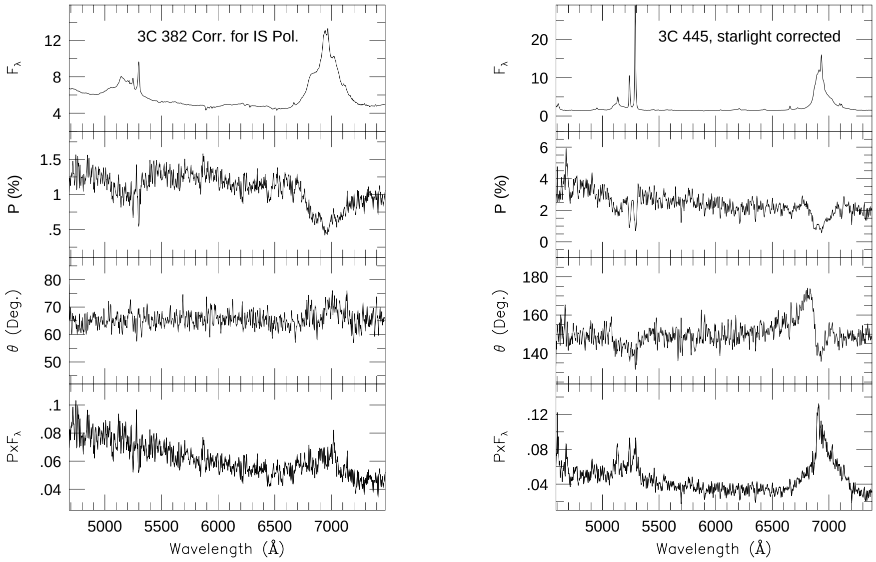

Figure 2. 3C 382 (left), 3C 445 (right)

3C 445 was observed for 5.3 hours and had the highest P of our set, but we have not yet obtained data to estimate the interstellar polarization. The flux spectrum has been corrected for a starlight fraction of 10% and for Galactic reddening (Fig. 2b). Here, too, the emission lines are polarized less than the continuum, at a different θ, and there is a change of about 30° across the Hα line. The polarization is thus not just due to a foreground screen, but is being generated on a relatively small scale. The asymmetry in P and θ also indicates some type of ordered flow in the emission line producing region; there would be no reason for this asymmetry if the emission lines were coming from clouds in random orbits. The polarized flux profile of Hα is similar to that of the direct flux. The data resembles those obtained for NGC 5548 (Martel 1996).

Pictor A and PKS 0921–213 were observed during the second test run of the new CTIO spectropolarimeter. The three sets of data on Pictor A are not in great agreement on the polarization, but it seems that the Hα line complex is unpolarized and the continuum may have slight polarization. For PKS 0921-213, the three sets of data again are not in great agreement with each other, but there is some measureable polarization across the Hα line complex and the continuum. The S/N is not good enough to engage in serious model fitting, but indicates the object is worth re-observing. This instrument is still under development and some hardware problems might explain the inconsistencies.

4. Discussion

The presence or absence of any polarization in the lines and/or the continuum can have implications about the path that photons follow from the source to the observer, without regard to specific models for the structure of the emitting region(s). The fact that the spectra (i.e., the continuum and the broad lines) of some objects with double-peaked emission lines, such as PKS 0921-213 and Pictor A, may be unpolarized suggests very strongly that Earth-bound observers have a direct view of the emitting regions. Both the continuum and the broad-line photons can reach the observer without scattering in intervening matter or matter associated with the central engine of the active nucleus.

In the context of models for an accretion disk origin of the broad, double-peaked lines, the absence of polarization implies that if there is a hydrostatic atmosphere or an outflowing wind over the disk, it has a negligible scattering optical depth in the Balmer lines. This should be contrasted with the spectropolarimetric data on Arp 102B (Antonucci et al. 1996), which show the Hα line has $P \sim 1\%$. The profile of the line in polarized light can be fitted with a model that attributes the polarization to scattering in an atmosphere of moderate optical depth overlaying the disk proper (Chen, Halpern, & Titarchuk 1997).

In the context of bipolar outflow (twin-jet) models (e.g., Zheng et al. 1990, 1991; Sulentic et al. 1995), the absence of polarization in the broad lines implies that the outflows themselves are optically thin and that there are no scattering regions in their vicinity that can act as mirrors. A plausible site of a mirror is a large cloud in the broad-line region which is either photoionized by a central source or shocked by the outflow itself. In this respect, the lack of polarization disfavors (although it does not rule out) the possibility that line emission from the outflow is powered by the release of kinetic energy via shocks since the shocks could give rise to mirrors.

In cases where polarization is detected (3C 382 & 3C 445), the continuum P is higher than the line P, suggesting that if the polarization results from scattering, the scattering medium is in the vicinity of the broad-line region. Additional information from the X-ray spectrum of 3C 382, which shows the signature of an ionized ("warm") absorber (Reynolds 1997), makes this an appealing interpretation. The ionization state and variability properties of the medium responsible for the absorption place it in the vicinity of the broad-line region, making it a good candidate for the scattering medium as well.

5. Conclusions

The polarization of 3C 390.3 may be largely interstellar. We do not see electron scattering as one might expect for an accretion disk model; perhaps the photons are arising from a very thin photoionized layer on the surface of the disk where the electron scattering optical depth is extremely small. We do not see scattering as suggested in outflow models: an optically thin outflow could be seen as optically thin on the side towards the observer, but on the red side we would be viewing material through the disk or reflected further down and thus would not appear optically thin.

In 3C 382 and 3C 445, we detect polarization in both the continuum and the lines, with Hα line polarizations of about 0.5-1.0%, but we do not see the predicted signature (in simple models) of disk emission in the polarized line profiles. Perhaps scattering in a medium surrounding the disk (and/or broad-line region) is responsible for the observed polarization, or the lines we are seeing in 3C 382 and 3C 445 do not come predominantly from a disk but from a "classical" broad-line region. The relatively flat continuum polarization and position angle in 3C 382 suggests that electron scattering is the polarization mechanism. In 3C 445 there is a rise to the blue in the continuum polarization, even after correction for starlight, and the continuum polarization position angle is flat. This is more suggestive of dust scattering, although bluer data would be helpful for strengthening this conclusion. In Pictor A, all three measurements are consistent with an Hα line polarization $\leq$ 0.1%. In PKS 0921–213, the polarization measured across Hα varied from $\sim$ 0.3% to 1.0%. Thus it is possible there is line polarization here, and more measurements could yield the S/N necessary for fitting the various models.

Acknowledgments. LK is supported by NSF International Research Fellowship INT-9423970 and NSF CAREER grant AST-9501835. ME acknowledges support from a Hubble Fellowship grant HF-01068.01-94A awarded by STScI. AMM acknowledges support from FAPESP and CNPq.

References

Antonucci, R. R. J. 1984, ApJ, 278, 499

Antonucci, R. R. J., Hurt, T., & Agol, E. 1995, ApJ, 456, L25

Chen, K., & Halpern, J. P. 1989, ApJ, 344, 115

Chen, K., & Halpern, J. P. 1990, ApJ, 354, L1

Chen, K., Halpern, J. P., & Titarchuk, L. G. 1997, ApJ, 483, 194

Corbett, E. A. , Robinson, A., Axon, D. J., Young, S., & Hough, J. H. 1998, MNRAS, 296, 721

Eracleous, M.a1988, in Structure and Kinematics of Quasar Broad Line Regions, ed. C. M. Gaskell, W. N. Brandt, D. Dultzin-Hacyan, M. Dietrich, & M. Eracleous (San Francisco: Astronomical Society of the Pacific), 000

Eracleous, M., & Halpern, J. P. 1994, ApJS, 90, 1

Eracleous, M., & Halpern, J. P. 1998, in preparation

Gaskell, C. M. 1983, in Quasars and Gravitational Lenses, Proc. 24th Liège Astrophysical Colloquium (Liège: Institut d'Astrophysique, Université de Liège), p. 473

Gaskell, C. M. 1996, ApJ, 464, L107

Halpern, J. P., & Eracleous, M. 1994, ApJ, 433, L17

Kay, L., Magalhães, M., Elizalde, E., & Rodrigues, C. 1998a, in prep.

Kay, L., Eracleous, M., Moran, E., Magalhães, M., & Halpern, J. 1998b, in preparation.

Martel, A. 1996, PhD Thesis, Univ. California, Santa Cruz

Oke, J. B. 1987, in Superluminal Radio Sources, ed. J. A. Zensus & T. J. Pearson (Cambridge University Press), 267

Pérez, E., Penston, M. V., Tadhunter, C., Mediavilla, E., & Moles, M. 1988, MNRAS, 230, 353

Reynolds, C. S. 1997, MNRAS, 286, 513

Simpson, C. J. 1994, D. Phil Thesis, University of Oxford

Stockton, A., & Farnham, T. 1991, ApJ, 371, 525
Sulentic, J. W., Marziani, P., Zwitter, T., & Calvani, M. 1995, ApJ, 438, L1
Zheng, W., Binette, L., & Sulentic, J. W. 1990, ApJ, 365, 115
Zheng, W., Veilleux, S., & Grandi, S. A. 1991, ApJ, 381, 418