RADIO-LOUD ACTIVE GALACTIC NUCLEI IN THE CONTEXT OF THE EIGENVECTOR 1 PARAMETER SPACE

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ABSTRACT

We consider the properties of radio-loud (RL) active galactic nuclei in the context of the eigenvector 1 (E1) parameter space. RL sources show a restricted E1 parameter space occupation relative to the radio-quiet (RQ) majority. The Fanaroff-Riley II “parent population” of relatively unboosted RL sources (median radio/optical flux ratio ~490) shows the most restricted occupation. RL sources have different broad-line properties (and inferred black hole masses and Eddington ratios). FWHM Hβ for the broad-line component in RL sources are at least twice as large as in the RQ majority. The average broad Fe II λ4570 emission-line strength is also about half that for RQ sources. Our sample suggests that the RL cutoff occurs near \( R_K \approx 70 \) or log \( P_{\text{radio}} \sim 32.0 \) ergs s\(^{-1}\) Hz\(^{-1}\). Sources below this cutoff are RQ, although we cannot rule out the existence of a distinct intermediate population. We show that the Doppler-boosted core-dominated RL sources (median flux ratio ~1000) lie toward smaller FWHM(Hβ) and stronger Fe II \( \lambda_{\text{opt}} \) in E1, as expected if the lines arise in an accretion disk. Our subsample of superluminous sources, with orientation inferred from the synchrotron self-Compton model, reinforce this general E1 trend and allow us to estimate the role of source orientation in driving E1 domain occupation.

Subject headings: galaxies: active — quasars: emission lines — quasars: general

1. INTRODUCTION

We recently presented an expanded spectroscopic database for 215 low-z active galactic nuclei (AGNs; Marziani et al. 2003a). The moderate signal-to-noise ratio (S/N) and resolution spectra cover the rest-frame region \( \approx 4300-5300 \) Å. Our expanded sample allows us to address a number of radio-loud (RL) issues that have been much discussed recently. We note that data with lower resolution or S/N cannot address these issues in an eigenvector 1 (E1; Sulentic et al. 2000a, 2000c) context because the uncertainties in line parameter measures will blur the trends that we find. An important issue involves claims that a RL versus radio-quiet (RQ) dichotomy does not exist (e.g., White et al. 2000; Cirasuolo et al. 2003) in measures of radio strength (i.e., radio power or radio/optical flux ratio). If distinct RL and RQ populations exist, quasar samples that use a radio selection criterion (e.g., FIRST) will be biased toward the bright end of the radio luminosity function (RLF) for RQ quasars. Therefore, a distribution of radio strength measures may not appear bimodal but simply with a small RL bump on the wing of the RQ source distribution. However, even if the distribution is not intrinsically bimodal and RQ and RL sources show a smooth, partly overlapping RLF, the RL/RQ dichotomy is appreciable in other properties.

2. THE RL SOURCES IN E1

There are two alternate approaches that may provide a much clearer answer to the issue of RQ-RL bimodality: (1) the E1 parameter space (Sulentic et al. 2000a, 2000c) and (2) considerations of radio source morphology in a classical unification scenario. The E1 diagram has the advantage that \( R_{\text{FeH}} \) and FWHM Hβ are not strongly dependent on luminosity up to at least \( M_B = -26 \) (Marziani et al. 2003a; correlation coefficients are \( \leq 0.1 \)). Therefore we can reasonably compare RQ and RL subsamples with different luminosity distributions in this parameter plane. Figure 1 shows the distribution in the optical E1 plane for all sources in our sample with log \( R_K > 1.0 \) (where \( R_K \) is the radio/optical flux ratio as defined in Kellermann et al. 1989). The bulk of our RL sources are concentrated in the region that we call Population B. Our RL sample is “unedited” and therefore shows a few sources with \( R_{\text{FeH}} > 0.4 \). These sources involve (1) our noisiest spectra, (2) sources with an extremely broad and very low EW Hβ broad component \( W_{\text{Hβ}} \approx 20 \) Å with a high upper limit for \( R_{\text{FeH}} \), and (3) a few luminous radio core-dominated (CD) sources \( \text{(circled)} \) that appear to be genuinely Fe II \( \lambda_{\text{opt}} \) strong and RL. The bulk of RL sources are restricted to the parameter ranges 3000 \( \leq \) FWHM(Hβ) \( \leq 10,000 \) km s\(^{-1}\) and 0 \( \leq R_{\text{FeH}} \leq 0.4 \).

Can the RL occupation in E1 be ascribed to sample selection effects? Systematic differences in FWHM Hβ between low-redshift RQ and RL AGNs are confirmed in samples in which \( z \) and apparent magnitude distributions are matched (Marziani et al. 2003b). Perhaps a large population of RL sources that will fill in E1 remains to be discovered, at least to the point of removing any difference in domain space occupation. While our sample is incomplete, it is certainly sampling a significant fraction of both RL and RQ sources brighter than \( V = 16.5 \) (see Fig. 2 in Marziani et al. 2003a).

It is unlikely that we have missed a major RL population with significantly different properties. At the same time, growing samples of narrow-line Seyfert 1 (NLSy1) sources (e.g., Grupe et al. 1999; we would call them extreme RQ Population A) contain almost no RL sources (see later discussion). The different RL domain space occupation in E1 argues in favor of a RL-RQ bimodality.

Figure 1 gives us more information because we have also examined the radio morphologies of all sources in our sample with log \( R_K \leq 1.0 \). The characteristic radio morphology of a classical RL source involves a double-lobed structure centered on a host galaxy (at low redshift) showing broad nuclear emission lines that mark it as hosting a type 1 AGN. Whether the central host can be seen or not, varying degrees of core radio emission are seen between the double lobes, with jet structure often con-
nnecting core and lobes. Double-lobed morphology in the context of type 1 AGNs usually means Fanaroff-Riley (1974) type II (FR II) sources. We identify 39 FR II sources in our RL sample (seven are technically hybrid morphology radio sources following Gopal-Krishna & Wiita 2000). This is somewhat more than half of our RL sample (62 with log $R_\text{K} > 2.0$). The remaining RL sources in our sample show core or core-jet radio structure. In a classical morphology unification scenario, they are interpreted as double-lobed sources aligned to within $\pm 25^\circ$ of our line of sight. In order to keep our definitions simple, our CD sources show no evidence for double-lobed structure in any published radio map (this will depend on the spatial frequency sensitivity and dynamic range of available maps).

We interpret FR II sources as the parent population of RL AGNs. They are shown as open circles in Figure 1, and the vast majority show a strong concentration in the Population B domain of E1. These are unambiguously RL sources and all show log $R_\text{K} \geq 1.8$—we find three additional FR II sources with $1.8 \leq \log R_\text{K} \leq 2.0$. Until weaker FR II sources are found, we adopt $\log R_\text{K} \sim 1.8$ as the lower limit for classical RL sources (the three open circles with $\log R_\text{K} > 1.0$ on the right side of Fig. 1 will likely move into the Population B region with better data). We make this statement because the CD RL analogs to the FR II sources are interpreted as preferentially aligned sources. Their lobe/jet axis should be aligned within a few degrees to our line of sight. One observes rapid variability at many wavelengths, apparent superluminal motion in the radio structure, and Doppler boosting of the continuum emission (even swamping the emission lines in blazars). The latter effect is most relevant here, because in the simplest unification the CD RL sources should all be Doppler boosted, while the FR II sources will be unboosted or less boosted than CD sources. The same source viewed pole-on will show a larger $R_\text{K}$ value (dependent on the boosting factor; Ghisellini et al. 1993) than when viewed lobe-on. CD sources with log $R_\text{K} > 2.0$ are marked as filled squares in Figure 1. Median log $R_\text{K}$ values for our FR II and CD subsamples are 2.7 and 3.0, respectively, with large scatter. The restricted domain space occupation for RL sources, compared to RQ sources, in E1 is perhaps the strongest argument for interpreting RL sources as being fundamentally different from the RQ majority of type 1 AGNs. At the very least, it implies that they are, in some sense, an extremum in a continuous sequence of type 1 AGN broad-line region (BLR) properties.

Figure 1 provides even more information, because we can now compare FR II and CD domain occupation with predictions of the favored models for low-ionization broad (including Balmer)-line emission. Our E1 motivated working hypothesis has been that (1) highly accreting (as supported by E1 parameters involving a C IV $\lambda 1549$ blueshift and a soft X-ray excess), low black hole (BH) mass Population A sources (Sulentic et al. 2000c; Marziani et al. 2001, 2003b) show Balmer and Fe II opt emission from an accretion disk, while (2) the larger BH masses and lower accretion rates estimated for RL + Population B RQ sources (Marziani et al. 2001, 2003b) coupled with the absence of a C IV $\lambda 1549$ blueshift and soft X-ray excess implied different disk/wind properties and probably a single emitting region (Marziani et al. 2003c). Claims of no RL-RQ mass difference (e.g., Oshlack, Webster, & Whiting 2002) may reflect smaller measured FWHM values resulting from nonsubtraction of a narrow component from the Balmer lines—$M_{\text{BH}} \propto [\text{FWHM}(\text{Fe } II_{\lambda 4570})]^2$.

We have suggested that the stronger Balmer line and weaker Fe II opt emission from Population B RL and RQ sources might be ascribed to thermal gas entrained along the jet axis (i.e., a bicone). In a bicone-dominated emission-line scenario, we would expect to see the broadest Balmer profiles in sources oriented near pole-on. A model viewing line emission from an accretion disk would make the opposite prediction—the Balmer lines would be narrowest for near face-on–oriented CD sources (see also Wills & Browne 1986). We would also expect stronger Fe II opt emission from a line-emitting disk when it is viewed face-on (Marziani et al. 2001). We would therefore expect RL CD sources to be displaced toward lower FWHM($\text{H}\beta_{\text{opt}}$) and larger $R_\text{Fe}$ in a disk scenario. It is clear from Figure 1 that a disk model is favored, since most CD sources are found at the lower edge of the FR II distribution and displaced toward slightly higher average $R_\text{Fe}$. E1 has enabled us to isolate the parent FR II RL population and to estimate the role of source orientation in driving RL source occupation.

### 2.1. Superluminal RL Sources in E1

We find a domain space separation between FR II and CD sources in E1. Following the same line of reasoning, we can examine the superluminal sources in our sample. Jet orientation can be inferred from radio observations that allow estimation of the synchrotron self-Compton flux relative to the observed X-ray flux (Ghisellini et al. 1993). Using the same reasoning, Rokaki et al. (2003) compared FWHM($\text{H}\alpha$) measures with predictions of jet orientation ($\theta$) and estimated Doppler boosting factor ($\delta$) for a sample of superluminal sources. They find a weak correlation consistent with the notion that the Balmer lines arise from an accretion disk whose plane is roughly perpendicular to the jet axis.

Figure 2 shows our $\theta$ versus FWHM($\text{H}\beta_{\text{opt}}$) correlation dia-
open circles/filled squares

sample of Marziani et al. (2003a).

plus two additional superluminals (NGC 1275 and 3C 345) from the

for nine superluminal sources common between our sample and Rokaki et al.

respectively). FWHM(Hα)

Asterisks: Hα measures from Rokaki et al.;

open circles/filled squares: our Hδ[FeII] measures (for lobed and pure core sources, respectively). FWHM(Hδ[FeII]) errors as in Fig. 1. The most deviant point (B2 1721+34) shows a peculiar Hδ[FeII] profile dominated by a very BLR component—it is not certain to have a classical BLR component (see Sulentic et al. 2000b).

program for nine superluminal sources in common with Rokaki et al. plus two additional sources from Marziani et al. (2003a). Our optical Hδ[FeII] measures are generally higher resolution and have a higher S/N than the IR Hα measures yielding a lower scatter. We confirm their conclusion that the correlation is consistent with a disk origin for the bulk of Balmer broad-line emission and that the correlation is opposite of that expected in a bicone scenario. The diagonal arrow in Figure 1 indicates the average expected change in E1 position due to change in orientation from FR II to CD sources. Many of the extreme boosted sources will be lineless blazars and hence absent from E1. It is interesting that BL Lac in a low continuum phase showed FWHM(Hα)

We have found a significant number of radio “intermediate” sources (1 \leq \log R_K \leq 2) and seek to account for them. At least five interpretations can be proposed. (1) The overlap between the faint end of the RLF for RL sources and the bright end of the RLF for RQ sources. This is supported by the data, since three sources show classical FR II structure—they are the weakest RL sources in our sample at R_K \approx 70. This is the simplest explanation and is further supported by a study of the 6–20 cm spectral indices (Ivezić et al. 2002), where it is concluded that almost all low-redshift RL AGNs are likely to show log R_K \approx 2.0. Assuming a mean value of log R_K \approx -0.05 for RQ sources and a reasonably symmetric distribution about the mean would place the high log R_K end of the distribution near 0.0. Explanation 2 can then be helpful here. (2) Mixed starburst/AGN sources with radio emission amplified by processes unrelated to the RL jet phenomenon. A good place to look would

3. DISTRIBUTION OF RQ AND RL SOURCES IN R_K:

RADIO INTERMEDIATES?

Figure 3 plots R_K versus the two optical E1 parameters. We again identify the FR II and CD RL populations as in Figure 1. We extracted 6 cm radio fluxes and optical B magnitudes from Veron-Cetty, Veron, & Gonçalves (2001). Similar distributions are found if one uses NRAO VLA Sky Survey (NVSS) 20 cm fluxes or if one uses radio power instead of R_K for the abscissa. The RL source preference for FWHM(Hδ[FeII]) \geq 4000 km s^{-1} and R_K \leq 0.5 is clearly seen in the plots. We also see a source deficit between \log R_K = 1.0 and 2.0. We do not suggest that this is the distribution that one would expect for any complete sample. It will never look like this for reasons discussed earlier.

RL sources are clearly overrepresented in our sample for complex reasons. The focus of interest here involves the most radio ambiguous sources between log R_K = 1.0 and 2.0. Three of them turned out to be FR II sources that define our lower boundary for the classical RL sources. In our interpretation, CD sources with R_K less than the weakest observed FR II sources have no meaning in a RL classical unification. Since all but three intermediate sources (n = 10 marked as filled triangles in Fig. 1) show core structure, we interpret their radio emission as unrelated to RL core/lobe emission. E1 further supports this interpretation because sources with log R_K < 1.0 show no domain preference; they are found just as frequently in the RQ Population A domain as in the Population B domain preferred by RL sources.

We have found a significant number of radio “intermediate” sources (1 \leq \log R_K \leq 2) and seek to account for them. At least five interpretations can be proposed. (1) The overlap between the faint end of the RLF for RL sources and the bright end of the RLF for RQ sources. This is supported by the data, since three sources show classical FR II structure—they are the weakest RL sources in our sample at R_K \approx 70. This is the simplest explanation and is further supported by a study of the 6–20 cm spectral indices (Ivezić et al. 2002), where it is concluded that almost all low-redshift RL AGNs are likely to show log R_K \approx 2.0. Assuming a mean value of log R_K \approx -0.05 for RQ sources and a reasonably symmetric distribution about the mean would place the high log R_K end of the distribution near 0.0. Explanation 2 can then be helpful here. (2) Mixed starburst/AGN sources with radio emission amplified by processes unrelated to the RL jet phenomenon. A good place to look would...
be among ultraluminous infrared galaxy (ULIRG) sources. We find many $R_\text{K}$ values between $\pm$ 1.0 with the most extreme sources (e.g., Arp 220 and NGC 6240) lying between 1.0 and 2.0. We can identify four objects among our 13 intermediate sources that show an IR excess and are interpreted as mixed AGN/starbursts (Mrk 231, IRAS 0759+64, NGC 7674, and Mrk 896) consistent with enhanced radio emission from activity related to star formation. If a plausibility correction ($A_g \approx 3.0$) for internal extinction is applied, e.g., to Mrk 231, then the observed log $R_\text{K}$ $\approx$ 1.8 will decrease to $\approx$ 0.6. Most of the remaining six intermediate sources are too distant for an IRAS detection below ULIRG level. (3) A population of RQ sources that show weak radio jet structure (Falcke, Gopal-Krishna, & Biermann 1995; Falcke, Sherwood, & Patnaik 1996; de Diego et al. 1998; Blundell & Rawlings 2001). This represents another method to enhance the radio emission from RQ sources. Could they be related or unrelated to classical RL activity? The domain occupation in E1 and the lack of double-lobed morphology argue that they are “unrelated.” (4) Population B spiral galaxies that are similar to elliptical hosted RL sources in BH mass, accretion rate, E1 parameters, and consequently, BLR structure, although with their radio emission beamed but somehow muffled. This interpretation is clearly related, or even identical, to explanation 3 (see references for explanation 3). Reliable host galaxy morphology exists only for a handful of our sources, but at least two known spirals in our sample show true RL (log $R_\text{K}$ $\approx$ 2) activity 3C 120 (complex core/jet emission—also called an FR I source) and III Zw 2. (5) Proto-RL sources that have not yet produced jet/lobe structure and are heavily self-absorbed (O’Dea 1998).

The remaining six intermediate sources are more difficult to explain. If we interpret these CD sources as classical RL AGNs, then they should be oriented with the jet axis near our line of sight and consequently beamed (Doppler-boosted). Such low $R_\text{K}$ values for boosted sources would imply an unbeamed parent population that is unambiguously RQ. One does not observe classical double-lobed sources in RQ samples (Kellermann et al. 1994; Kukula et al. 1998). The intermediate sources show Population B properties with mean FWHM(H$\alpha_{\text{BC}}$) $\approx$ 8800 km s$^{-1}$ and $R_{\text{K, BC}}$ $\approx$ 0.3. These sources deserve further study in order to see if they conform to any of the possible explanations proposed above.

Have we so far missed many radio intermediate sources in our growing sample? The simplest reason would be if a class of low-redshift intermediate radio emitters was shown to be optically fainter on average than low-redshift populations of RQ and RL sources. One must be careful here, because any optical dimming will tend to enhance rather than diminish $R_\text{K}$. That would point toward a RQ parent population for the dimmed sources by the same argument that radio weak/intermediate CD sources viewed as beamed sources imply a weaker (i.e., RQ) parent population.

We note that three NLSy1 galaxies (not part of our sample) with log $R_\text{K}$ $\approx$ 1.4, 1.5, and 1.8 (Remillard et al. 1986; Siebert et al. 1999; Grupe et al. 2000) have been proposed as CD RL sources. They would fall in the (Population A) intermediate region of Figure 1, where RL sources are rare. They do not fit in a classical RL unification scheme but may be candidate-beamed RQ sources. PKS 2004$-$447 (Oshlack et al. 2001) shows narrow Balmer lines and no Fe $\lambda_{\text{opt}}$ emission and is probably a type 2 AGN. As far as we are aware, Zhou et al. (2003) have found the first genuinely RL NLSy1 source (log $R_\text{K}$ $>$ 3.0)—it would fit with the three Fe $\lambda_{\text{opt}}$ strong CD sources circled in Figure 1.

4. CONCLUSION

We find that (1) E1 parameters support some kind of dichotomy between RL and RQ AGNs, (2) sources with different radio morphology occupy different regions of the E1 parameter space, supporting the unification assumption that true RL CD sources can be interpreted as almost face-on FR II sources, and (3) E1 occupation and comparison of superluminal source orientation estimates with E1 parameters suggest that a significant part of the Balmer and Fe $\lambda_{\text{opt}}$ emission arises in an accretion disk. The latter result suggests that the RL-RQ dichotomy may be more related to evolution than to fundamentally different BLR structure.

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