AGN Physics with the Sloan Digital Sky Survey
*ASP Conference Series, Vol. **VOLUME***, 2004*
G.T. Richards and P.B. Hall, eds.

Quasar Radio Dichotomy: Two Peaks, or not Two Peaks, that is the Question

Željko Ivezić, Gordon T. Richards, Pat B. Hall, Robert H. Lupton, Anjoli S. Jagoda, Gillian R. Knapp, James E. Gunn, Michael A. Strauss, David Schlegel, William Steinhardt, Robert J. Siverd

Dept. of Astroph. Sciences, Princeton University, Princeton, NJ 08544

Abstract. Recent claims by Ivezić et al. (2002) that the distribution of the radio-to-optical flux ratio, R, for quasars is bimodal (the so-called quasar radio dichotomy) were questioned on statistical grounds by Cirasuolo et al. (2003). We apply the approach suggested by Cirasuolo et al. to a sample of $\sim 10,000$ objects detected by SDSS and FIRST, and find support for the quasar radio dichotomy. The discrepancy between the claims by Cirasuolo et al. and the results presented here is most likely because 1) the ∼100 times larger sample based on two homogeneous surveys that is used here allows a direct determination of the R distribution, rather than relying on indirect inferences based on Monte Carlo simulations of several heterogeneous surveys 2) the accurate SDSS colors and redshift information allow robust determination of the K-correction for R, which, if unaccounted for, introduces significant scatter that masks the intrinsic properties of the quasar R distribution.

1. What Statistics to Use?

There is controversy in the literature about the existence of a bimodality in the distribution of radio-to-optical flux ratio, R, for quasars (the so-called quasar radio dichotomy). For example, White *et al.* (2000) suggested that previous detections of radio dichotomy were caused by selection effects. On the other hand, Ivezić et al. (2002, hereafter I02) claimed that a sample of quasars detected by the SDSS and FIRST surveys supports the existence of a radio dichotomy. The latter result was recently questioned on statistical grounds by Cirasuolo et al. (2003, hereafter C03). I02 determined the distribution of $R_i = 0.4\,(i - t)$ for narrow regions in the t (radio AB magnitude) vs. i (optical magnitude) plane that were oriented perpendicular to the R_i=const. lines (see top left panel in Figure 1). In other words, the quasar density in the t vs. i plane, $\rho(i,t)$, was found to be a separable function $\rho(i,t) = f(R_i)\,g(i+t)$. The R_i distribution, $f(R_i)$, determined this way has a strong maximum at $R_i \sim 2$, and declines towards smaller R_i (bottom left panel in Fig. 1). Since a large majority ($\sim$ 90%) of quasars undetected by FIRST form another peak at $R_i < 0$, the local minimum at $R_i \sim$ 0–1 implies the existence of a radio-dichotomy.

C03 claimed that a more meaningful quantity is the conditional probability distribution $p(R_i|i)$, that is, the R_i distribution for a given (narrow range of) i, with $\rho(i,t) = p(R_i|i)\,n(i)$. Here $n(i)$ is the differential i distribution ("optical

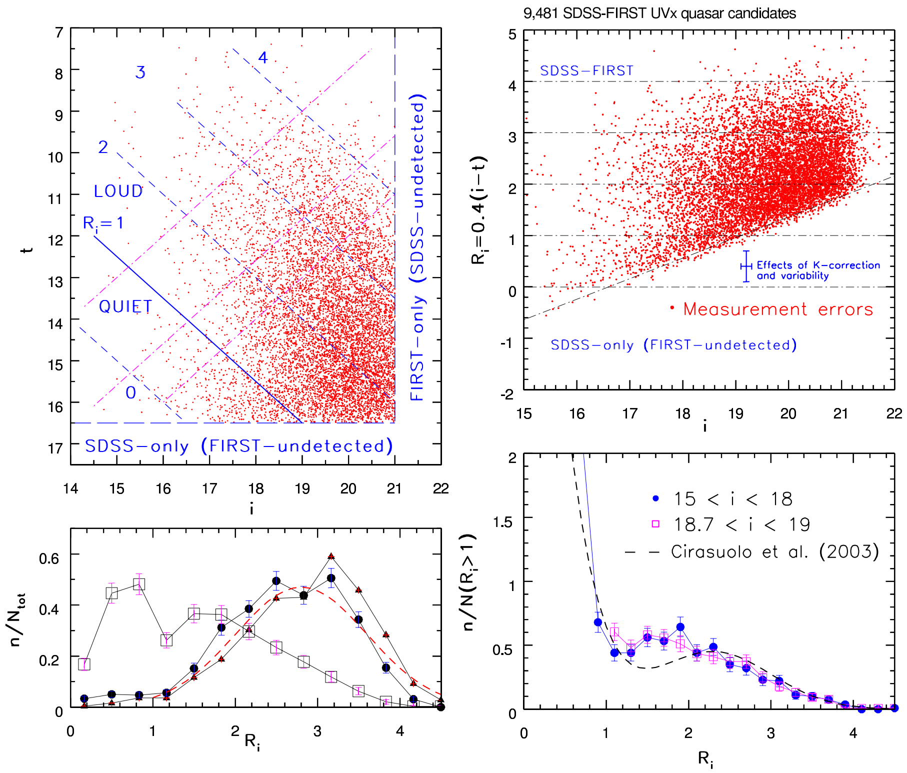

Figure 1. The two left panels summarize the analysis of the quasar radio dichotomy by Ivezić et al. (2002), and are repeated here with a ∼3 times larger sample from SDSS and FIRST (∼10,000 objects). In the top left panel, which shows the source distribution in the t (radio AB magnitude) vs. i (optical magnitude) plane, the diagonal dot-dashed lines define regions that were used to determine the $R_i = 0.4\,(i-t)$ distribution. The R_i histograms for these regions, marked by filled circles and triangles in the bottom left panel, were interpreted as evidence for a quasar radio dichotomy. The histogram marked by open squares shows the R_i distribution for sources with $i < 18$, and is shown as an example of a biased estimate of the R_i distribution. The upper right panel shows the R_i vs. i distribution for the same SDSS-FIRST data set as in the two left panels (note that this diagram is a sheared, and not simply a rotated, version of the diagram in the top left panel). The large dot in the top right panel illustrates the typical measurement uncertainty. The error bars show the uncertainty in R_i (∼0.2-0.3) mostly due to optical and radio K-corrections, and in i (∼0.1 mag), due to optical variability. The two histograms in the bottom right panel (symbols with error bars) show $p(R_i|i)$ for two ranges of i, as marked. The dashed line in the bottom right panel shows a best-fit result for $p(R_i|i)$ by Cirasuolo et al. (2003), displayed here for illustration (it is shifted left by 0.4 mag to account for different optical bands, i vs. B).

counts"). For comparison with their work, in this contribution we analyze the behavior of $p(R_i|i)$. In the top right panel in Figure 1, we show the R_i vs. i distribution for ∼10,000 quasar candidates detected by both SDSS and FIRST (for more details see York 2000, I02, Schneider et al. 2003, and references therein). The corresponding $p(R_i|i)$ displayed in the bottom right panel does not decrease smoothly with R_i; rather, it suggests a possible local minimum around $R_i \sim 1.2$, and a local maximum around $R_i \sim 1.8$. This distribution is consistent with the C03 best-fit shown by the dashed line in the lower right panel (the latter is in fact a bimodal function). Note that, given the FIRST flux limit shown as the diagonal dot-dashed line in the top right panel, only quasars *brighter* than $i \sim 19$ can be used to directly constrain the position of the local minimum in $p(R_i|i)$, and thus a large area optical survey such as SDSS is required (as opposed to a deeper survey of a smaller area).

2. To K-correct, or not?

When analyzing the R_i distribution, it is important to realize that the scatter due to K-corrections and quasar variability is much larger than the measurement errors. The uncertainty in R_i (∼0.2-0.3) is mostly due to optical and radio flux K-corrections, and optical variability. Even if the intrinsic R_i were the same for all quasars (i.e. a δ-function), its observed distribution would still have a finite width because of this uncertainty. In practice, this effect smears any features in R_i distribution and would reduce any bimodality, if not taken into account.

The need to account for the K-correction can be inferred from the improved agreement between different R_i histograms when the sample is divided into redshift bins. We compared the $p(R_i|i)$ distributions in different redshift bins using the *uncorrected* R_i, and found them to be systematically different. Furthermore, the differences between the $p(R_i|i)$ distributions for different i bins in a given narrow redshift bin are smaller than when the whole redshift range is considered. This systematic behavior disappears when a proper K-correction for R_i is applied.

We determined the K-correction for R_i, such that $R_i^{corr} = R_i^{obs} + \Delta R_i$, as

$$\Delta R_i = (\alpha_{radio} - \alpha_{optical}) \log(1+z), \tag{1}$$

where α_{radio} and $\alpha_{optical}$ are radio and optical spectral slopes, respectively ($F_\nu \propto \nu^\alpha$). We use the difference between $g-i$ color for a particular source and the median $g-i$ color at the redshift of that source to estimate the optical spectral slope (Richards et al. 2003). For radio spectral slope we assume α_{radio} = -0.5, which is the median value of radio spectral index for a sample of ∼400 quasars with SDSS, GB6, FIRST, NVSS and WENSS detections (Ivezić et al., in prep.).

3. Evidence for Quasar Radio Dichotomy

Figure 2 compares the distribution of SDSS-FIRST quasars with redshifts in the range 0.5–2.5 in the R_i vs. i plane when R_i is **not** K-corrected (left), and when R_i **is** K-corrected using eq. 1 (right). As evident in the bottom panels, accounting for K-correction increases the significance of the detected bimodality. It is important to use an estimate of the optical spectral slope on an *object-by-object* basis – it is insufficient to use a mean slope as obtained from e.g. a composite quasar spectrum.

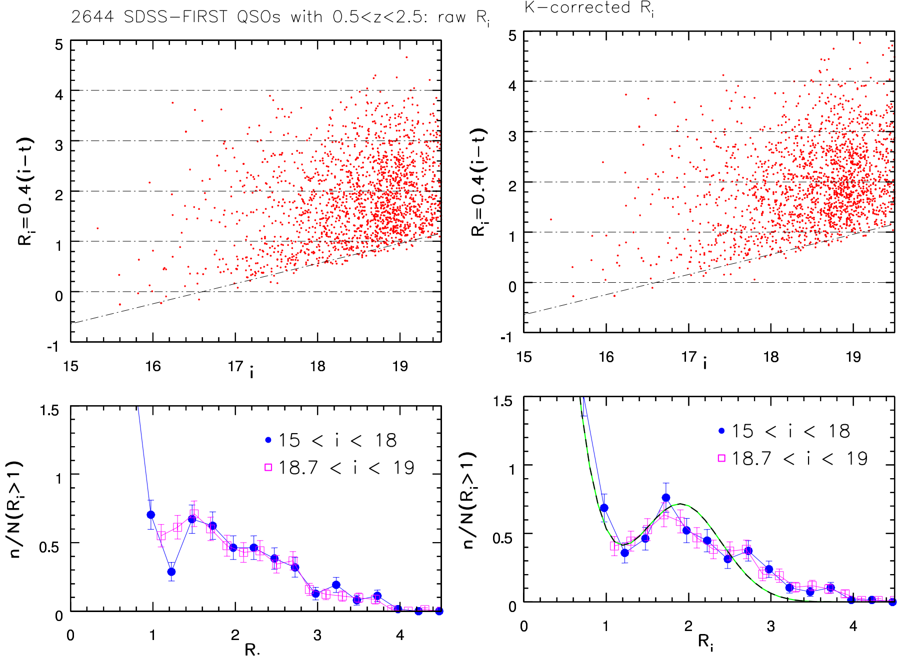

Figure 2. The two left panels show the R_i vs. i and $p(R_i|i)$ distributions for quasars with $0.5 < z < 2.5$ in two i magnitude bins, where R_i is **not** K-corrected. The two right panels show analogous results when R_i **is** K-corrected using eq. 1. The thick line in the bottom right panel is the best-fit using the same functional form as proposed by C03 (a double Gaussian). It has a local minimum at $R_i \sim 1.2$ and a local maximum at $R_i \sim 1.9$, with the maximum-to-minimum ratio of ∼2.

The dashed line in the bottom right panel in Figure 2 is the best-fit using the same functional form proposed by C03 (a double Gaussian). It has a local minimum at $R_i \sim 1.2$ and a local maximum at $R_i \sim 1.9$, with the maximum-to-minimum ratio of ∼2. As reported by Ivezić et al. (2002), the fraction of sources with $R_i > 1$ is 8±1 %. The remaining 92% of quasars, most of which are not detected by FIRST, are responsible for the steep rise of $p(R_i|i)$ for $R_i < 1$.

We conclude that accurate optical and radio measurements for a large and homogeneous sample of radio quasars obtained by SDSS and FIRST provide conclusive evidence for the existence of the quasar radio-dichotomy.

Funding for the creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the National Science Foundation, the U.S. Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS Web site is http://www.sdss.org/.

References

Cirasuolo, M., et al. 2003, astro-ph/0306415

Ivezić, Ž, et al. 2002, AJ, 124, 2364

Richards, G.T., et al. 2003, AJ, 126, 1131

Schneider, D.P., et al. 2003, AJ, in press, astro-ph/0308443

White, R.L., et al. 2000, ApJS, 126, 133

York, D.G., et al. 2000, AJ, 120, 1579