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CLEAR EVIDENCE FOR INTRANIGHT OPTICAL VARIABILITY IN RADIO-QUIET QUASARS

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ABSTRACT

We present new clues to the problem of the radio loudness dichotomy arising from an extensive search for intranight optical variability in seven sets of optically luminous radio-quiet quasars and (radio-loud) BL Lacertae objects, which are matched in optical luminosity and redshift. Our monitoring of radio-quiet quasars has for the first time clearly detected such intranight variability, with peak-to-peak amplitudes ~1%, occurring with a duty cycle of $\sim\frac{1}{6}$. The matched BL Lac objects have both higher variability amplitudes and duty cycles when observed in the same fashion. We show that the much less pronounced intranight variability of the radio-quiet quasars relative to BL Lac objects can be understood in terms of a modest misalignment of the jets in radio-quiet quasars from the line of sight. We thus infer that relativistic particle jets may well also emerge from radio-quiet quasars, but while traversing the short optical-emitting distances, they could be snuffed out, possibly through inverse Compton losses in the nuclear region.

Subject headings: BL Lacertae objects: general — galaxies: active — galaxies: jets — quasars: general — quasars: individual (1029+329, 1252+020)

1. INTRODUCTION

The dichotomy of radio emission from quasars has been a persistent hurdle in developing a general theoretical framework for the emission from active galactic nuclei (AGNs). Whereas the powerful jets of relativistic particles are believed to be generic to the central engines of the radio-loud subset (e.g., Antonucci 1993; Urry & Padovani 1995), the situation remains confused as to the existence of such jets in the radio-quiet majority of quasars (e.g., Antonucci, Barvainis, & Alloin 1990; Sopp & Alexander 1991; Terlevich et al. 1992; Stein 1996; Ivezić et al. 2002).

Intranight optical variations (INOVs) of blazars, established by using CCDs as N star photometers (e.g., Miller, Carini, & Goodrich 1989; Carini et al. 1992; Noble et al. 1997), are now generally linked to the presence of relativistic jets (e.g., Marscher, Gear, & Travis 1992; Wagner & Witzel 1995; Noble et al. 1997). Equally clear signatures of jets have been lacking for radio-quiet quasars (RQQs), despite several searches for INOV in luminous RQQs (Gopal-Krishna, Wiita, & Altieri 1993; Gopal-Krishna, Sagar, & Wiita 1995; de Diego et al. 1998; Rabbette et al. 1998; Gopal-Krishna et al. 2000). Although radio observations have revealed faint, aligned structures in a handful of RQQs (Miller, Rawlings, & Saunders 1993; Kellermann et al. 1994; Papadopoulos et al. 1995; Kukula et al. 1998; Blundell & Rawlings 2001), the case for relativistic jets as a generic feature of RQQs remains unsettled (Sopp & Alexander 1991; Wilson & Colbert 1995; Stein 1996; Kukula et al. 1998).

In our earlier papers, statistical evidence for intranight optical fluctuations was presented for some RQQs (Gopal-Krishna et al. 1995, 2000; Sagar, Gopal-Krishna, & Wiita 1996), but in no case was it overwhelmingly convincing. The results of several independent studies have been discrepant and hence inconclusive (Jang & Miller 1995, 1997; de Diego et al. 1998; Rabbette et al. 1998; Romero, Cellone, & Combi 1999). Jang & Miller (1995, 1997) claimed detection of INOV in far more BL Lac objects than in radio-quiet AGNs from a heterogeneous sample. For the RQQs Ton 951 and Ton 1057, Jang & Miller (1995, 1997) presented differential light curves (DLCs) showing up to ~8% variations on hourlike timescales. However, optical luminosities of both these AGNs are modest ($M_B > -24.3$, taking $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$) and close to the critical value below which radio properties are thought to become like those of Seyfert galaxies (Miller, Peacock, & Mead 1990). At these lower levels of AGN/galactic light ratios, false indications of variability, produced by seeing variations that include different amounts of host galactic light within the photometric aperture, become very probable (Cellone, Romero, & Combi 2000). Romero et al. (1999) monitored a sample of 23 southern objects: eight RQQs and 15 blazars. None of their eight RQQs was clearly found to vary down to 1% rms, while nine of their 15 blazars showed INOV above that level. Rabbette et al. (1998) also failed to detect INOV in a sample of 23 high-luminosity RQQs, but their detection threshold was ~0.1 mag. In contrast to these tentative results implying little INOV for RQQs, de Diego et al. (1998) concluded that microvariability is at least as common among RQQs (six detections in 30 sessions) as it is among the (relativistically beamed) core-dominated radio-loud quasars (CDQs; five in 30), commonly deemed as blazars along with BL Lac objects. Each of their 17 RQQs had a CDQ counterpart of nearly matching brightness and redshift. The observational and analysis procedures of de Diego et al. (1998) differ radically from those of all other programs, including ours. They usually monitored each object only a few (three to nine) times per night at intervals of ~30 minutes; they divided each of these observations into five, roughly 1 minute each, exposures. De Diego

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TABLE 1
The Sample of Radio-quiet Quasars and BL Lac Objects[a]

Set Number	Object	Other Name	Type	B	M_B	z	N[b]	Observation Durations (h) and Variability Status[c]
1	0945+438	US 995	RQQ	16.45	−24.3	0.226	3	8.0 (NV), 6.3 (NV), 6.6 (NV)
	1215+303	B2 1215+30	BL	16.07	−24.8	0.237	4	7.0 (V, 5.5, 3.5), 5.9 (NV), 5.0 (NV), 6.8 (V, 4.9, 1.8)
2	0514−005	1E 0514−0030	RQQ	16.26	−25.1	0.291	3	5.3 (NV), 5.8 (NV), 7.5 (NV)
	1215+303	B2 1215+30	BL	16.07	−24.8	0.237	4[d]	7.0 (V, 5.5, 3.5), 5.9 (NV), 5.0 (NV), 6.8 (V, 4.9, 1.8)
3	1252+020	Q 1252+0200	RQQ	15.48	−26.2	0.345	5	6.4 (V, 3.3, 2.3), 6.1 (NV), 4.3 (V, 3.6, 0.9), 4.6 (NV), 7.3 (NV)
	0851+202	OJ 287	BL	15.91	−25.5	0.306	4	6.8 (V, 2.8, 2.3), 5.6 (V, 6.5, 3.8), 4.2 (V, 5.8, 5.0), 6.9 (V, 2.7, 2.8)
4	1101+319	TON 52	RQQ	16.00	−26.2	0.440	4	8.5 (NV), 5.6 (NV), 6.1 (V, 2.6, 1.2), 5.8 (NV)
	0735+178	PKS 0735+17	BL	16.76	−25.4	>0.424	4	7.8 (NV), 7.4 (NV), 6.0 (NV), 7.3 (V, 2.8, 1.0)
5	1029+329	CSO 50	RQQ	16.00	−26.7	0.560	5	5.0 (NV), 5.3 (V, 4.3, 1.3), 5.8 (NV), 8.5 (NV), 6.8 (V, 3.8, 1.2)
	0219+428	3C 66A	BL	15.71	−26.5	0.444	7	6.5 (V, 6.0, 5.4), 5.7 (V, >6.6, 5.5), 9.1 (V, 5.8, 4.3), 10.1 (V, 3.5, 3.2), 9.0 (V, 2.9, 2.2), 5.1 (NV), 5.1 (V, >6.6, 8.0)
6	0748+294	QJ 0751+2919	RQQ	15.00	−29.0	0.910	6	7.6 (NV), 8.3 (NV), 5.1 (NV), 5.4 (NV), 6.0 (NV), 5.4 (NV)
	0235+164	AO 0235+164	BL	16.46	−27.6	0.940	3	6.6 (V, >6.6, 12.8), 6.2 (V, 3.2, 10.3), 7.9 (V, 2.6, 7.6)
7	1017+279	TON 34	RQQ	16.06	−29.8	1.918	3	7.3 (NV), 7.1 (NV), 8.1 (NV)

[a] Data are taken from Véron-Cetty & Véron 1998.
[b] Number of nights of observation.
[c] NV = not variable, V = variable; when V, followed by $C_{\rm eff}$ and ψ(%)-values.
[d] Data taken from set 1, which also includes this BL Lac object.

et al. (1998) used small (∼2″) apertures and estimated their errors through an analysis of variance technique that involved only one comparison star. Compared to those of other groups, these techniques lead to less trustworthy results.

2. OBSERVATIONS

Motivated by the need to look for a signature of relativistic nuclear jets in intrinsically luminous, bona fide RQQs, we launched in 1998 a program of R-band monitoring of seven sets of bright ($m_B \sim 16$) AGNs, each set falling in a narrow redshift bin between $z = 0.17$ and 2.2 and consisting of an RQQ, a BL Lac object (except in the highest z bin), a CDQ, and a radio lobe-dominated quasar. Thus, the four AGN classes in the sample are matched in the z-M_B plane. We monitored each of the AGNs on at least three nights, taking approximately five exposures per hour, for durations between 4 and 8 hr per night. This program required 113 nights during 1998–2002, details of which are presented elsewhere (Stalin 2002; Gopal-Krishna et al. 2003, in preparation). Here we summarize the main results obtained for the RQQs and BL Lac objects over the course of 53 nights of observations (Table 1). All seven RQQs are not only optically luminous, $(-24.3 \geq M_B \geq -29.8)$ but also genuinely radio-quiet, with $R < 1$, where R is the rest-frame ratio of 5 GHz to 250 nm flux densities (Stocke et al. 1992).

The R-band CCD observations were made using the 1.04 m Sampurnanand telescope of the State Observatory, Naini Tal, India. At least two, but usually more, comparison stars, similar in brightness to the target AGNs, were present on each (bias-subtracted, flat-fielded) CCD frame. We derived DLCs of the AGNs relative to these comparison stars and also for all the pairs of comparison stars. Thus, we identified and discounted any comparison stars that themselves varied.

Photometry of the AGNs and the comparison stars was carried out using the same circular aperture, and the instrumental magnitudes were determined using the PHOT task in IRAF.[2] For each night, a range of aperture radii was considered, and the one that minimized the variance of the DLC of the steadiest comparison star pair was accepted. The typical aperture radius used was 4″; however, the DLCs are not very sensitive to the chosen radius. Variations exceeding 0.01 mag over the night can be readily detected on these DLCs.

[2] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

3. RESULTS

Figure 1 shows the DLCs of two of the RQQs, 1029+329 ($R < 0.2$) and 1252+020 ($R = 0.5$) (Table 1). In each case, the DLCs of the RQQs against all three comparison stars (*top three panels*) are consistent in showing a gradual fading by ∼1% over 4–5 hr, whereas the simultaneous DLCs involving the same three comparison stars are steady to within ∼0.3%.

Conceivably, the decline in the DLCs of the RQQs could be an artifact of the color difference, $\Delta C_{\rm QS}$, between the RQQ and the comparison stars, leading to a differential attenuation with varying zenith distance (i.e., air mass). However, this possibility can be discounted, since no such systematic fading is evident on the star-star DLCs shown in the two bottom panels in Figure 1, for which the color difference is comparable to $\Delta C_{\rm QS}$ (except for a brief flare seen near 17.3 UT in the DLC for the star pair S2-S1, which is clearly attributable to a variation of star S2). Another potential caveat is that a systematic variation in the point-spread function (PSF) could have led to a varying contribution from the RQQ host galaxy within the photometric aperture (Cellone et al. 2000). This possibility can also be excluded, since the host galaxy is expected to contribute less than 10% of the flux of each of these luminous RQQs and is also expected to be encompassed well within the ∼4″ aperture radius used. In addition, we have determined the PSF for the successive CCD frames using the comparison stars and find that the PSF actually narrowed progressively by ≃1″ over both of these nights. This implies that the actual fadings of the two RQQs are marginally larger than those recorded on the DLCs (Fig. 1). We conclude that the observed INOV of these two RQQs, although small, is real. All these checks have not been employed in earlier studies, so these two cases with well-resolved brightness gradients represent the clearest evidence reported so far for intranight variability of luminous RQQs. (Similar reasoning is applicable to all the cases of INOV reported here.) The results for the RQQs and BL Lac objects in the sample are summarized in Table 1.

There exists a wide discrepancy between the reported duty cycles (DCs) of INOV for RQQs vis-à-vis BL Lac objects/blazars (Jang & Miller 1997; de Diego et al. 1998; Romero et al. 1999). Contributions to the DCs are weighted by the number

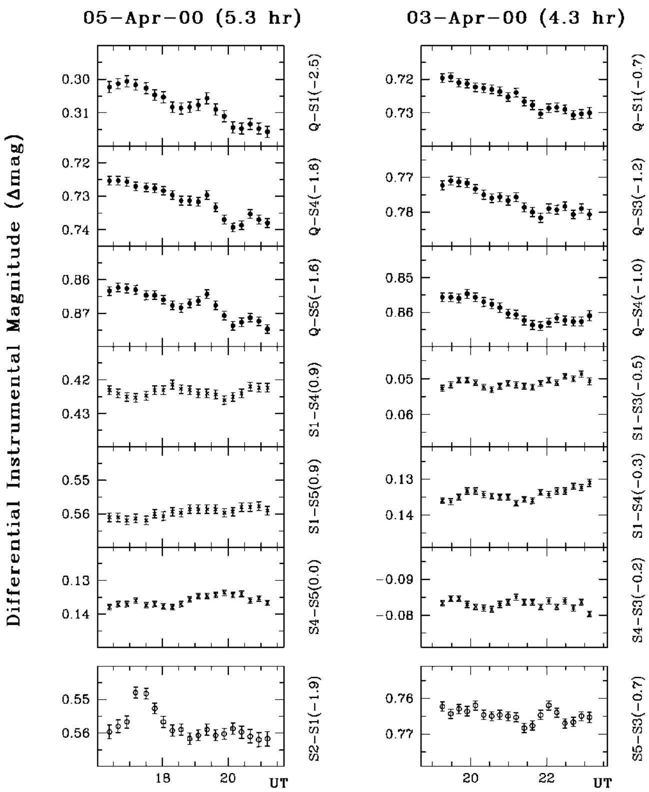

FIG. 1.—*R*-band DLCs for the RQQs 1029+329 (*left*) and 1252+020 (*right*), derived using aperture radii of 4″.1 and 3″.6, respectively. The top three panels show the DLCs of each RQQ relative to the three comparison stars, while the next three panels below display the DLCs for the comparison stars, as labeled on the right side. The bottom panel for each RQQ shows the DLC for a star pair, also present on the CCD frames, for which the differential $B-R$ color is comparable to that for the DLCs of the corresponding RQQ. The J2000.0 coordinates of the stars in the left panels are: S1 ($10^h32^m8^s.94$, +32°37′50″.7), S2 ($31^m59^s.46$, 41′56″.1), S4 ($32^m7^s.50$, 37′28″.1), and S5 ($31^m57^s.24$, 39′19″.8). The corresponding values for the stars in the right panels are: S1 ($12^h55^m21^s.00$, +01°41′13″.9), S3 ($55^m33^s.90$, 45′20″.9), S4 ($55^m15^s.60$, 43′54″.9), and S5 ($55^m36^s.06$, 42′4″.4). The numbers inside the parentheses to the right of the DLCs are the differences between the ($B-R$) colors of the corresponding pair of objects (as taken from the USNO-A2.0 catalog at http://archive.eso.org/skycat/servers/usnoa).

of hours (in the rest frame) for which each source was monitored (Romero et al. 1999),

$$\mathrm{DC} = 100\,\frac{\sum_{i=1}^{n} N_i(1/\Delta t_i)}{\sum_{i=1}^{n}(1/\Delta t_i)}\,\%, \qquad (1)$$

where $\Delta t_i = \Delta t_{i,\,\mathrm{obs}}(1+z)^{-1}$ is the duration (corrected for cosmological redshift) of a monitoring session of the source in the selected class; N_i equals 0 or 1, if the object was nonvariable or variable during Δt_i, respectively.

For RQQs, counting only the sessions for which INOV was positively detected (Table 1), we find that DC = 17%. This can be compared with DC = 72% determined here for the BL Lac objects. Our data also allow, for the first time, estimation of DC for different ranges of peak-to-peak variability amplitude, $\psi \equiv [(D_{\max} - D_{\min})^2 - 2\sigma^2]^{1/2}$. Here D is the differential magnitude, $\sigma^2 = \eta^2\langle\sigma_{\mathrm{err}}^2\rangle$, with η the factor by which the average of the measurement errors (σ_{err}, as given by the PHOT algorithm) should be multiplied; we find $\eta = 1.50$ (Stalin 2002; Gopal-Krishna et al. 2003, in preparation). The results are given in Figure 2. All the RQQs have $\psi < 3\%$, and for

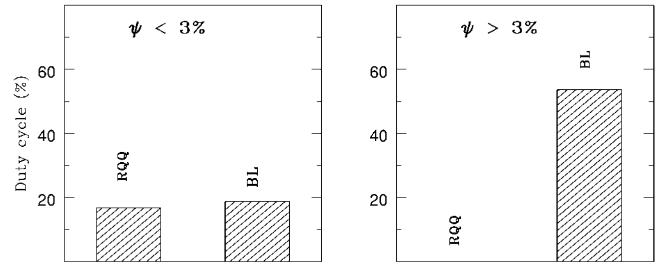

FIG. 2.—DCs of the INOV of the RQQs and BL Lac objects (as determined using the DLCs for all the RQQs and BL Lac objects in our sample), for two ranges of peak-to-peak variability amplitude, ψ (see text). The seven RQQs were observed on 29 nights for a total of 185.8 hr; the five BL Lac objects, for 148.1 hr on 22 nights (Table 1).

$\psi < 3\%$, the DCs for BL Lac objects and RQQs are very similar. However, stronger INOV, with $\psi > 3\%$, is exclusive to the BL Lac objects (DC = 53%). Still, we note our sample is small, and it would be very useful to have similarly sensitive and careful measurements of a larger number of matched pairs to allow more confident estimates of DCs and distributions of ψ.

To quantify the variability, we have employed a statistical criterion based on the parameter C, similar to that followed by Jang & Miller (1997), with the added advantage that for each AGN we have DLCs relative to multiple comparison stars. This allows us to discard any variability candidates for which the multiple DLCs do not show clearly correlated trends, both in amplitude and time. We define C for a given DLC as the ratio of its standard deviation, σ_{T}, and the mean σ of its individual data points, $\eta\sigma_{\mathrm{err}}$. This value of C_i for the ith DLC of the AGN has the corresponding probability, p_i, that the DLC is steady (nonvariable), assuming a normal distribution. For a given AGN, we then compute the joint probability, P, by multiplying the values of p_i's for individual DLCs available for the AGN. The effective C parameter, C_{eff}, corresponding to P, is given in Table 1 for each variable AGN; our definition of variability is $C_{\mathrm{eff}} > 2.57$, which corresponds to a confidence level in excess of 99%. This is followed by the variability amplitude, ψ. We also note that for these AGNs all the DLCs between comparison stars were found to show statistically insignificant variability.

4. DISCUSSION AND CONCLUSIONS

To what extent can the observed INOV of RQQs be reconciled with the much more pronounced INOV of the BL Lac objects? Within the canonical jet picture, any flux variations associated with the relativistic outflow will have their timescales shortened and amplitudes boosted in the observer's frame. As usual, the Doppler factor is $\delta = [\Gamma(1 - \beta\cos\theta)]^{-1}$, where $\beta = v/c$, $\Gamma = (1-\beta^2)^{-1/2}$ is the bulk Lorentz factor of the jet, and θ is its viewing angle. Then the observed flux, S_{obs}, is given in terms of the intrinsic flux, S_{int},

$$S_{\mathrm{obs}} = \left(\frac{\delta}{1+z}\right)^p S_{\mathrm{int}}, \qquad (2)$$

where $p = (2 - \alpha)$ for a continuous jet (e.g., Urry & Padovani 1995); the spectral index $\alpha \equiv d\ln S_\nu / d\ln\nu$, and we have assumed $\alpha = -1$ (Stocke et al. 1992). Similarly, the beaming shortens the observed timescale to $\Delta t_{\mathrm{obs}} = \Delta t_{\mathrm{int}}(1+z)/\delta$.

The effect of Doppler beaming on the observed DLCs is illustrated in Figure 3, taking the example of the BL Lac object AO 0235+164, for which we found a large ($\psi \sim 13\%$) and rapid

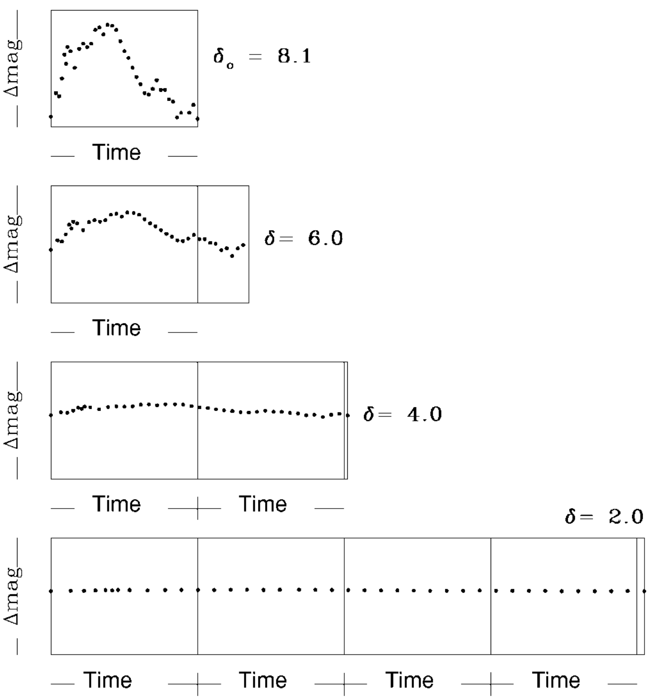

FIG. 3.—*Top panel*: *R*-band DLC from observations on 1999 November 12 of the BL Lac object AO 0235+164 for which $\delta_o = 8.1$ (Zhang et al. 2002). The remaining three panels show the DLCs simulated from the observed DLC, by applying a correction for Doppler debeaming appropriate to progressively lower values of δ (which involves an amplitude contraction and temporal stretching; see text). The total amplitude, Δmag, for each panel is 0.1 mag, and the indicated time duration of each frame in any of the four panels is 6.6 hr (in the observer's frame of reference).

($\tau \sim 3.5$ hr) variation on 1999 November 12. We use the estimated $\delta_o = 8.1$ for this object (Zhang, Fan, & Cheng 2002) to simulate the DLCs for lower values of δ, relevant to observers at larger viewing angles. This mapping is achieved simply by compressing the observed DLC amplitudes by $(\delta/\delta_o)^p$ and, simultaneously, stretching the DLC in time by a factor (δ_o/δ). From these simulated DLCs, it is evident that observers even marginally misaligned from the jet direction will monitor a drastically reduced INOV, both in amplitude and rapidity, for the same BL Lac object that appears highly variable to a somewhat better aligned observer (Fig. 3). For instance, if $\theta = 5°$ for the jet of AO 0235+164, the estimated $\delta_o = 8.1$ corresponds to $\beta = 0.978$. This would give $\delta \simeq 4$ and 2, respectively, for modestly misaligned viewing angles of $\theta = 15°$ and $\theta = 25°$, thought to be typical of RQQs (Antonucci 1993; Barthel 1989).

We thus suggest that the mere low level of intranight optical variability of RQQs in no way rules out their having optical synchrotron jets as active intrinsically as the jets of BL Lac objects. The large difference in the radio properties could arise from inverse Compton quenching of the jet in a majority of quasars, occurring beyond the very small physical scale probed by the nuclear optical synchrotron jet emission. A possible signature of such quenching is the hard X-ray spectral tail found in some RQQs (George et al. 2000). This emission from the (modestly misaligned) jets is seen despite the extremely strong forward flux boosting of the X-rays expected from the inverse Compton scattering of external (e.g., broad emission line) photons by the relativistic jet ($\propto\delta^{4-2\alpha}$; Dermer 1995). It remains possible that the weak fluctuations seen in RQQs arise from a different process, such as fluctuations from an accretion disk (e.g., Mangalam & Wiita 1993), while the larger ones seen only in BL Lac objects might originate from jets. Nonetheless, our observations and analysis lend some support to the concept of a jet-disk symbiosis (e.g., Falcke, Malkan, & Biermann 1995), where jets emerge ubiquitously from accretion flows; hence, the dichotomy between radio-loud and radio-quiet quasars need not imply a fundamental difference in their central engines.

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