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A Comparative Study of Intra-night Optical Micro-variability of High Luminosity AGN Classes

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Abstract. This thesis explores mainly the problem of the radio loudness dichotomy in quasars. This is addressed by carrying out an extensive search for intra-night optical variability (INOV) in seven sets of optically luminous radio-loud and radio-quiet quasars matched in the 'optical luminosity - redshift' plane from $z \simeq 0.2$ to $z \simeq 2.0$. Each set consists of a radio-quiet quasar (RQQ), a radio lobe-dominated quasar (LDQ), a radio core-dominated quasar (CDQ) and/or a BL Lac object (BL Lac). This work has for the first time provided convincing evidence of intra-night optical variability in RQQs. Based on clear detection of INOV, the duty cycles (DCs) are about 17% and 9% for RQQs and LDQs respectively. Another new result is a clear distinction we find between the INOV properties of the two types of relativistically beamed AGNs, with BL Lacs showing high DC of INOV (72%) compared to CDQs (20%). Also, BL Lacs generally show higher variability amplitudes (ψ) compared to the other three AGN classes. However, we find that ψ as well as the DC are similar for BL Lacs and the sub-set of CDQs with high (> 3%) optical polarization. This similarity in the DC and amplitude of INOV for RQQs, LDQs and CDQs suggests, firstly, that the radio loudness alone does not guarantee an enhanced INOV in QSOs and secondly, that as in LDQs, relativistic jets probably also exist in RQQs. We also demonstrate that the substantial differences in INOV properties of RQQs and LDQs as compared to BL Lacs can be explained in terms of special relativistic effects arising from our viewing the latter at small angles to the jet direction. Thus the mechanism producing the optical variations in radio-loud and radio-quiet AGNs can be very similar, and sub-parsec scale jets may well be present in all types of AGNs, obviating the need for any fundamental difference between the central engines of RQQs and radio-loud quasars.

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1. Introduction

Multi-wavelength studies of intensity variations of quasars have played a key role in probing the physical conditions near the centres of activity in the nuclei of galaxies and in placing powerful constraints on their models, especially when intra-night timescales are probed. Optical variability on hour-like timescales for blazars has been a well established phenomenon for over a decade (Miller, Carini & Goodrich 1989). A related outstanding question is the dichotomy between radio-loud quasars (RLQs) and radio-quiet quasars (RQQs). In the jet dominated subset of RLQs, usually denoted as blazars, variability is strong in essentially all electromagnetic bands, and is commonly associated with the non-thermal Doppler boosted emission from jets (e.g. Blandford & Rees 1978; Marscher & Gear 1985; Hughes, Aller & Aller 1992). Intra-night variability in blazars may well arise from instabilities or fluctuations in the flow of such jets (e.g. Marscher, Gear & Travis 1992).

As for RQQs, which follow the radio-far IR correlation defined for disk galaxies, it has been argued that starbursts make the dominant contribution to the radio output in these objects (e.g. Sopp & Alexander 1991; also, Terlevich et al. 1992). In this case, accretion disk instabilities may be responsible for any rapid fluctuations detected in RQQs (e.g. Mangalam & Wiita 1993; Kawaguchi et al. 1998). On the other hand, jet-like radio features, or faint radio structures, which in some cases extend far beyond the confines of the parent galaxy, have been detected in deep radio images of several RQQs, arguing for the existence of weak jets even in RQQs (e.g. Kellermann et al. 1994; Miller, Rawlings & Saunders 1993; Blundell & Rawlings 2001).

Two of the much debated and intriguing questions concerning AGN are the reality and origin of the apparent dichotomy in radio emission of QSOs. Although it has long been claimed that radio-loud quasars are only a small fraction (10–15%) of all QSOs, an analysis of the FIRST radio survey results (White et al. 2001) argued that the claimed dichotomy was an artefact of selection effects and that there was a continuous distribution in radio loudness. In contrast, another recent study of the correlations between the FIRST radio and preliminary SDSS optical surveys found that the dichotomy is real and that radio-loud sources are about 8% of the total QSO population (Ivezić et al. 2002). While the observational situation remains confused, a large number of models have been put forward to explain this RL/RQ dichotomy. One set of models argues the dichotomy is due to differences in the hosts of the quasars, but recent HST observations reveal that RQQs are also frequently found in elliptical hosts and so there is little difference in the environments of these two QSO populations (see, Dunlop et al. 2003 and references therein). The other set of models argue this dichotomy is due to the two QSO populations having fundamentally different central engines, such as: (i) more rapidly spinning black holes produce powerful relativistic radio jets (e.g. Blandford 2000; Wilson & Colbert 1995); (ii) radio emission correlates with the mass of the nuclear black hole (e.g. Dunlop & McLure 2002); (iii) RLQs have binary BHs (Sillanpää 1999); and (iv) difference of accretion rate and possible changes in the accretion mode (e.g. McLure & Dunlop 2001).

2. Motivation and the Sample

Environments of the central engines of quasars probed using VLBI on parsec scales show clear differences between radio-loud and radio-quiet quasars, with RLQs exhibiting (relativistic) jets. However, direct structural information is lacking about the environments of the two population of quasars on much smaller scales (~ 1 light-hour), as it is beyond the reach of any existing imaging telescope. Flux variability observations on intra-night time-scales can serve as a uniquely efficient tool to probe such smaller scales. The major motivation of this thesis is to examine if there are any fundamental differences between the central engines of radio-loud and radio-quiet quasars, which are manifested on the inner scales (light-day/light-hour). This is pursued by carrying out a systematic and temporally dense intra-night optical monitoring of a matched sample of radio-loud and radio-quiet quasars.

The sample of AGNs used in this thesis work consists of seven sets of quasars taken from the catalog of Véron-Cetty & Véron (1998) covering a total redshift range from $z = 0.18$ to $z = 2.2$. Each set consists of a RQQ, a LDQ, a CDQ and/or a BL Lac of similar magnitude and redshift, bright enough ($B < 17$) to yield good S/N in < 10 min and luminous enough ($M_B < -24.3$) to definitely qualify as a quasar. Our final sample consists of 26 QSOs (a BL Lac is common to sets 1 and 2 and no BL Lac is available for the highest redshift set No. 7). Data on these objects are given in Table 1, where R is the calculated K–corrected radio to optical flux ratio, as per Stocke et al. (1992).

3. Observations and Basic Reductions

The observations used the 104-cm Sampurnanand telescope of the State Observatory, Naini Tal which is an RC system with a f/13 beam (Sagar 1999) during the period October 1998 – May 2002. A total of 113 nights (720 hours) were devoted to this project, an average of 6.5 hours per night of observation. The detector used was a cryogenically cooled 1024 × 1024 CCD chip (prior to October 1999) and a 2048 × 2048 chip (after October 1999) mounted at the cassegrain focus. Each pixel of both the CCDs correspond to 0.38×0.38 arcsec^2 on the sky covering a total field of $12' \times 12'$ ($6' \times 6'$) in the case of the larger (smaller) CCD. Observations were nearly always done using an R filter, as it was near the maximum response of the CCD detector system and thus allowed us to achieve good temporal resolution. To improve S/N, observations were carried out in 2 × 2 binned mode. On each night only one QSO was monitored as continuously as possible. The typical sampling rate was about 5 frames per hour, the choice of the exposure time depending on the brightness state of the QSO, the moon's phase and sky transparency, so that variations of even ~ 1% could be detected. The QSO field was centered so as to contain at least 2 but usually 3 comparison stars (within about a magnitude of the QSO) on the CCD frame.

Preliminary processing of the images as well as photometry was done using the IRAF software. Photometry of the QSO and a few comparison stars recorded on the same CCD frame was carried out using the *phot* task in IRAF. The same circular aperture was used for the photometry of the QSO and the comparison stars for all the images acquired over the night. This optimum

Table 1. Properties of the seven sets of quasars monitored in this programme

Set No.	Object	Type	RA(2000)	Dec(2000)	B (mag)	M_B (mag)	z	log R
1.	0945+438	RQQ	09 48 59.4	+43 35 18	16.45	−24.3	0.226	< −0.7
	2349−014	LDQ	23 51 56.1	−01 09 13	15.45	−24.7	0.174	2.47
	1309+355	CDQ	13 12 17.7	+35 15 23	15.60	−24.7	0.184	1.36
	1215+303	BL	12 17 52.0	+30 07 01	16.07	−24.8	0.237	2.63
2.	0514−005	RQQ	05 16 33.5	−00 27 14	16.26	−25.1	0.291	<0.06
	1004+130	LDQ	10 07 26.2	+12 48 56	15.28	−25.6	0.240	2.29
	1128+315	CDQ	11 31 09.4	+31 14 07	16.00	−25.3	0.289	2.43
	1215+303	BL	12 17 52.0	+30 07 01	16.07	−24.8	0.237	2.63
3.	1252+020	RQQ	12 55 19.7	+01 44 13	15.48	−26.2	0.345	−0.28
	0134+329	LDQ	01 37 41.3	+33 09 35	16.62	−25.2	0.367	3.93
	1512+370	CDQ	15 14 43.0	+36 50 50	16.25	−25.6	0.370	3.57
	0851+202	BL	08 54 48.8	+20 06 30	15.91	−25.5	0.306	3.32
4.	1101+319	RQQ	11 04 07.0	+31 41 11	16.00	−26.2	0.440	< −0.41
	1103−006	LDQ	11 06 31.8	−00 52 53	16.39	−25.7	0.426	2.80
	1216−010	CDQ	12 18 35.0	−01 19 54	16.17	−25.9	0.415	2.34
	0735+178	BL	07 38 07.4	+17 42 19	16.76	−25.4	>0.424	3.55
5.	1029+329	RQQ	10 32 06.0	+32 40 21	16.00	−26.7	0.560	< −0.64
	0709+370	LDQ	07 13 09.4	+36 56 07	15.66	−26.8	0.487	2.08
	0955+326	CDQ	09 58 20.9	+32 24 02	15.88	−26.7	0.530	2.74
	0219+428	BL	02 22 39.6	+43 02 08	15.71	−26.5	0.444	2.83
6.	0748+294	RQQ	07 51 12.3	+29 19 38	15.00	−29.0	0.910	−0.68
	0350−073	LDQ	03 52 30.6	−07 11 02	16.93	−27.2	0.962	3.07
	1308+326	CDQ	13 10 28.7	+32 20 44	15.61	−28.6	0.997	2.71
	0235+164	BL	02 38 38.9	+16 37 00	16.46	−27.6	0.940	3.29
7.	1017+279	RQQ	10 19 56.6	+27 44 02	16.06	−29.8	1.918	< −0.49
	0012+305	LDQ	00 15 35.9	+30 52 30	16.30	−29.1	1.619	1.76
	1225+317	CDQ	12 28 24.8	+31 28 38	16.15	−30.0	2.219	2.26

aperture for photometry was selected by considering a range of apertures starting from the median FWHM over the night and choosing that aperture which produced the minimum variance in the star – star differential light curve (DLC) of the least variable pair of comparison stars. Details of the observations and reductions are in Stalin et al. (2003a). DLCs of the AGN relative to the selected comparison stars as well as between all pairs of the comparison stars are constructed from the derived instrumental magnitudes, and are used to look for the presence of INOV in the AGN. The choice of more than one comparison star for the differential photometry enables us to reliably identify AGN variability, as any of the comparison stars which themselves varied during the night could be identified and discarded.

4. Analysis and Results

Intra-night optical monitoring of all classes of objects in our luminosity and redshift matched sample was carried out with comparably high sensitivities and for similar durations. This work

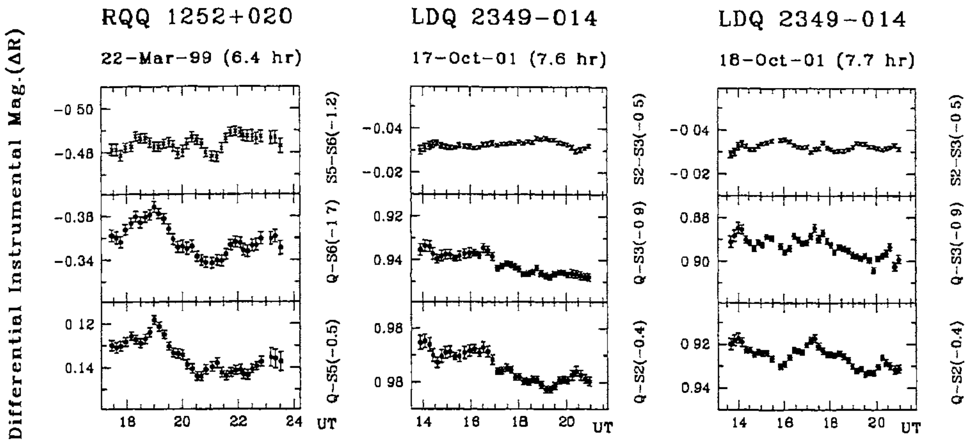

Figure 1. DLCs of one of the RQQs and one of the LDQs in our monitoring program with positive detections of INOV. The name of the QSO, the date and the duration of observations are given in the top of each panel. The upper panel gives the DLC of the comparison stars themselves, whereas the bottom two panels give the DLCs of the QSO relative to both the comparison stars as defined in the labels on the right side. The numbers inside the parentheses are the differential colour indices, Δ(B−R) for the respective DLCs

reports for the first time a systematic study of the INOV characteristics of the various AGN classes, and has placed on a firm footing the phenomenon of optical intra-night variability of optically luminous quasars of both non-blazar types (RQQs and LDQs). Sample DLCs are shown in Fig. 1. Details on the non-blazar AGNs monitored in this program can be seen in Gopal-Krishna et al. (2003) and Stalin et al. (2003b) and for the blazar class of AGNs in Sagar et al. (2003).

Duty cycles (DCs) of INOV were calculated following the definition of Romero et al. (1999). Since most AGNs do not exhibit variability on each night, duty cycles are best estimated not as a fraction of the variable objects found within a given class, but as the ratio of the time over which objects of the class are seen to vary, to the total observing time spent on monitoring the objects in that class:

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

where $\Delta t_i = \Delta t_{i,obs}(1+z)^{-1}$ is the duration (corrected for cosmological redshift) of an i^{th} monitoring session of the AGN out of a total of n sessions employed for that AGN class; N_i equals 0 or 1, depending on whether the AGN was non-variable or variable, respectively, during Δt_i. For RQQs, counting only the sessions for which INOV was positively detected, we find that DC = 17%. Similarly we find a DC of 9% for LDQs (including the two cases of possible detection raises this to 15%) and 20% for CDQs with typical errors in the DCs of about 6%. This can be compared with DC = 72% determined for the BL Lacs, which agrees to within 10% with several other independent studies of BL Lacs (see Romero et al. 1999). The results are shown in

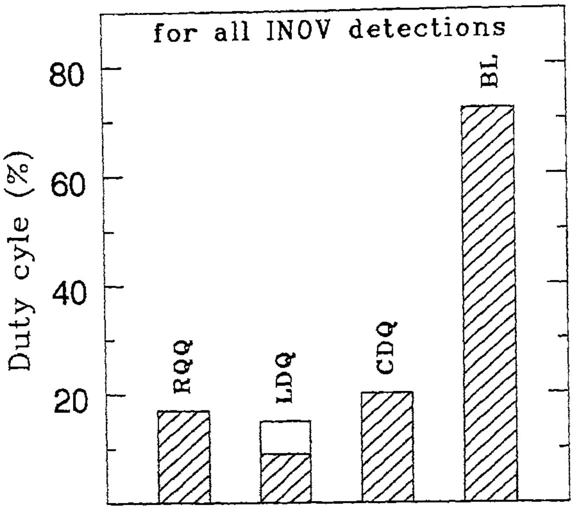

Figure 2. Duty cycle for various classes of AGNs for all variability amplitudes. The shaded bars refer to definite detections of INOV, whereas the non-shaded portion includes the contribution of possible detections of INOV.

Fig. 2. 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, $\sigma^2 = \eta^2 < \sigma^2_{\rm err} >$, with η the factor by which the average of the measurement errors ($\sigma_{\rm err}$, as given by *phot* algorithm) should be multiplied; we find $\eta = 1.50$ (cf. Stalin et al. 2003a). All the RQQs are found to have $\psi < 3\%$, and for $\psi < 3\%$, the DCs for BL Lacs and RQQs are very similar. However, stronger INOV, with $\psi > 3\%$, is exclusive to the BL Lacs (DC = 53%).

Interestingly, the range of INOV amplitudes for both RQQs and LDQs are found to be very similar ($\psi < 3\%$). This similarity of the INOV characteristics of RQQs and LDQs *vis-à-vis* BL Lacs can be explained within the conventional relativistic jet paradigm if one postulates that such jets exist (on optically emitting scale lengths) in all classes of AGNs, including RQQs. This has been demonstrated through simulated lightcurves in Gopal-Krishna et al. (2003) and Stalin et al. (2003b). Confining our attention to the two of the total six CDQs in our sample which have high (> 3%) optical polarization, we find that they resemble BL Lacs in both DC and the amplitude of INOV. It thus appears that INOV is primarily associated with optical polarization, which itself is believed to be associated with shocks in relativistic jets (e.g. Marscher & Gear 1985; Hughes, Aller & Aller 1992). The large difference in the radio properties could arise from inverse Compton quenching of jets in the majority of QSOs at some distance 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)

5. Conclusions

1. The present work has shown for the first time clear evidence of optical intra-night variability in RQQs.
2. The non-blazar type AGNs, *viz* RQQs and LDQs, are found to show similar INOV characteristics, both in INOV amplitude and duty cycle (DC).
3. There is a significant difference in the INOV duty cycle of CDQs and BL Lacs. BL Lacs show high DC of ~72% in contrast to CDQs which show a DC of only ~20%. The amplitudes of variation of BL Lacs are also larger, many having $\psi > 3\%$.
4. Considering only the CDQs which show high (> 3%) optical polarization, we find that they resemble BL Lacs in both the DC and amplitude of INOV. Thus it appears that the mere presence of a prominent (and hence Doppler boosted) radio core does not guarantee INOV. Rather it appears that the more crucial factor for INOV is the optical polarization of the core emission. Such polarized emission is normally associated with shocks in relativistic jets.
5. Even though the percentage luminosity variations implied by the INOV for these luminous AGNs is small, the total power involved is still so enormous as to render a starburst/supernova explanation untenable at least for these rapid events.
6. We argue the the mere low level of INOV in RQQs does not rule out their having optical synchrotron jets as active intrinsically as the jets of BL Lacs. So our observations support the scenario where jets emerge ubiquitously from accretion flows and the radio-loudness dichotomy of quasars need not necessarily imply a fundamental difference in the central engines of radio-loud and radio-quiet quasars.

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References

Blandford R., Rees M. J., 1978, in Wolfe A. M., ed, *Pittsburgh Conference on BL Lac Objects*, Pittsburgh U., p. 328

Blundell K. M., Rawlings S., 2001, ApJ, 562, L5

Blandford R., 2000, Phil. Trans. Roy. Soc. London, Sec. A., (astro-ph/0001499)
Dunlop J.S., McLure R.J., 2002 (astro-ph/0203184)
Dunlop J.S., et al. 2003, MNRAS, 340, 1095
George I. M., et al., 2000, ApJ, 531, 52
Gopal-Krishna, Stalin C. S., Sagar R., Wiita P. J., 2003, ApJL, 586, L25
Hughes P., Aller H., Aller M., 1992, ApJ, 396, 469
Ivezić, Z., et al., 2002, AJ, 124, 2364
Kawaguchi, T., Mineshige, S., Umemura, M., Turner, E. L., 1998, ApJ, 504, 671
Kellermann K. I., Sramek R. A., Schmidt M., Green R. F., Shaffer D. B., 1994, AJ, 108, 1163
Marscher A. P., Gear W. K., 1985, ApJ, 298, 114
Marscher A. P., Gear W. K., Travis J. P., 1992, in Valtaoja E., Valtonen M., eds, *Variability of Blazars*, CUP, Cambridge, p. 85
Mangalam A. V., Wiita P. J., 1993, ApJ, 406, 420
McLure R. J., Dunlop J., 2001 in Marquez I., et al., eds, *QSO Hosts and their Environments*, Kluwer, Dordrecht, p. 27
Miller H. R., Carini M. T., Goodrich B. D., 1989, *Nature*, 337, 627
Miller P., Rawlings S., Saunders R., 1993, MNRAS, 263, 425
Romero, G. E., Cellone, S. A., Combi, J. A., 1999, A&AS, 135, 477
Sagar R., 1999, Current Science, 77, 643
Sagar R., Stalin C. S., Gopal-Krishna, Wiita, P. J. 2003, MNRAS in press (astro-ph/0306392)
Sillanpää A. K., in S. K. Chakrabarti ed. *Observational evidence for black holes in the Universe*, Kluwer, Dordrecht, p. 209
Sopp H. M., Alexander P., 1991, MNRAS, 251, 14P
Stalin C. S., Gopal-Krishna, Sagar R., Wiita P. J., 2003a, submitted to JAA (astro-ph/0306395)
Stalin C. S., Gopal-Krishna, Sagar R., Wiita P. J., 2003b, MNRAS submitted (astro-ph/0306394)
Stocke J. T., Morris S. L., Weymann R. J., Foltz C. B., 1992, ApJ, 396, 487
Terlevich R., Tenorio-Tagle G., Franco J., Melnick J., 1992, MNRAS, 255, 713
Véron-Cetty M.-P., Véron P., 1998, ESO Scientific Report No. 18
White R. L., et al., 2001, ApJS, 126, 133
Wilson A. S., Colbert E. J. M., 1995, ApJ, 438, 62