Mon. Not. R. Astron. Soc. **000**, 1–?? (2004) Printed 2 February 2008 (MN LaTeX style file v2.2)

Intra-night Optical Variability of BL Lacs, Radio-Quiet Quasars and Radio-Loud Quasars

C. S. Stalin[1,2], Alok C. Gupta[3], Gopal-Krishna[4,5], Paul J. Wiita[6], and Ram Sagar[2,7]

[1] *IUCAA, Post Bag 4, Ganeshkhind, Pune 411 007, India*
[2] *State Observatory, Manora Peak, Naini Tal 263 129, India*
[3] *Harish-Chandra Research Institute, Chhatnag Road, Jhunsi, Allahabad 211019, India*
[4] *National Centre for Radio Astrophysics, TIFR, Pune University Campus, Post Bag 3, Pune 411 007, India*
[5] *Institut d'Astrophysique de Paris, 98 bis, Bd. Arago - 75014, Paris, France*
[6] *Department of Physics & Astronomy, Georgia State University, P.O. Box 4106, Atlanta, Georgia 30302-4106, USA*
[7] *Aryabhatta Research Institute of Observational Sciences, Manora Peak, Nainital 263 129, India*

Accepted 2004 xxxxx. Received 2004 xxxxx

ABSTRACT

We report monitoring observations of 20 high-luminosity AGN, 12 of which are radio-quiet quasars (RQQs). Intra-night optical variability (INOV) was detected for 13 of the 20 objects, including 5 RQQs. The variations are distinctly stronger and more frequent for blazars than for the other AGN classes. By combining these data with results obtained earlier in our program, we have formed an enlarged sample consisting of 9 BL Lacs, 19 RQQs and 11 lobe-dominated radio-loud quasars. The moderate level of rapid optical variability found for both RQQs and radio lobe-dominated quasars argues against a direct link between INOV and radio-loudness. We supplemented the present observations of 3 BL Lacs with additional data from the literature. In this extended sample of 12 well observed BL Lacs, stronger INOV is found for the *EGRET* detected subset.

Key words: BL Lacertae objects – galaxies: active – galaxies: jets – galaxies: photometry – quasars: general

1 INTRODUCTION

In a series of papers since 2003, we have reported results of a program to search for intra-night optical variability (INOV; see Wagner & Witzel 1995 for a review), often called microvariability, in a sample of 26 optically luminous active galactic nuclei (AGN), using the 104-cm Zeiss telescope of the Aryabhatta Research Institute of Observational Sciences (ARIES), Naini Tal, India (Gopal-Krishna et al. 2003, GK03; Stalin et al. 2004a, St04a; Sagar et al. 2004, Sa04; Stalin et al. 2004b, St04b; see also Stalin 2003). These objects belong to the four major classes of luminous AGN, namely, radio-quiet QSOs (RQQs), radio-loud lobe-dominated quasars (LDQs), radio-loud core-dominated quasars (CDQs), and BL Lac objects (BLs). The sample selection was such that the four classes are reasonably well matched in the z–M_B plane, with z ranging from 0.17 to 2.2 and M_B ranging from -24.3 to -30.0 (taking $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$).

The observations under this program typically achieved convincing detectability of INOV at a level of 0.01–0.02 mag and spanned a total of 113 nights (720 hours) between October 1998 and May 2002. This work provided the first positive detection of INOV for RQQs, though modest evidence for such variations had been obtained earlier (e.g. Gopal-Krishna et al. 1995, 2000; Sagar et al. 1996; Jang & Miller 1997). It was, moreover, found that except for BLs and high optical polarization CDQs (HP-CDQs), the amplitude of detected INOV is small ($\leqslant$ 3 per cent) and so is the INOV duty cycle (∼10–20 per cent), *irrespective of the radio loudness*. Further, for the BLs and HP-CDQs, for which a strong INOV was frequently observed, no correlation was found between the amplitude of INOV and long-term optical variability (St04b). We argued that these results are consistent with the hypothesis that even radio-quiet QSOs possess relativistic jets emitting optical emission on sub-parsec scales, but that we are observing them at moderately large angles to the jet direction so that any variations are neither amplified in magnitude nor compressed in time-scale as they are in BL Lacs (GK03; St04a). Wills (1996) also argued that RQQs do indeed possess jets, but that they propagate through denser gas close to the host galaxies' planes and are thus quickly snuffed out. For BLs we found no correlations between apparent brightness levels and INOV properties (St04b). This is in accord with a recent study which indicates that microvariability of a blazar may be correlated with the presence of longer-term flux changes, rather than its apparent brightness level (Howard et al. 2004).

Table 1. The sample of 20 optically luminous AGN monitored in the present work

IAU Name	Type	B	M_B	z	P_{opt} † (%)	log R^* ‡
0003+158	LDQ	16.51	−25.7	0.450	0.65	2.6
0025+307	LDQ	15.79	−26.7	0.500	—	1.8
0043+039	RQQ	16.00	−26.0	0.385	0.27	−0.7
0806+315	BL	15.70	−25.0	0.220	—	1.7
0824+098	RQQ	15.50	−25.6	0.260	—	0.5
0832+251	RQQ	16.10	−25.5	0.331	—	0.1
0846+513	CDQ	16.28	−29.4	1.860	—	2.2
0850+440	RQQ	16.40	−26.1	0.513	—	< -0.5
0931+437	RQQ	16.47	−25.8	0.456	—	0.1
0935+416	RQQ	16.31	−29.6	1.966	—	< -0.7
0945+438	RQQ	16.28	−24.5	0.226	—	< -0.1
1029+329	RQQ	16.00	−26.7	0.560	—	< -0.6
1418+546	BL	16.17	−23.7	0.152	7.5	3.1
1422+424	RQQ	16.42	−25.1	0.316	—	< -0.4
1425+267	LDQ	15.78	−26.0	0.366	1.9	2.0
1444+407	RQQ	15.45	−25.7	0.267	0.4	−1.1
1522+101	RQQ	16.20	−28.4	1.324	0.3	< -0.7
1553+113	BL	15.00	−26.8	0.360	—	2.2
1631+395	LDQ	16.48	−27.8	1.023	1.1	1.6
1750+507	RQQ	15.80	−25.6	0.300	—	0.7

† References for optical polarization: Wills et al. 1992; Berriman et al. 1990; — for no data available
‡ R^* is the K-corrected ratio of the 5 GHz radio to 2500 Å-band optical flux densities (Stocke et al. 1992); references for radio fluxes: Véron-Cetty & Véron 2001; NVSS (Condon et al. 1998); FIRST (Becker et al. 1995; Bauer et al. 2000)

In this paper, we present the results of our optical monitoring for another 20 AGN belonging to all of the above mentioned four classes of luminous AGN. We then combine the present data for 3 BLs with similar high quality light-curves for another 9 BLs taken from literature, to arrive at a representative sample of 51 intra-night optical light-curves for BL Lacs. This sample allows us to make a comparative study of the INOV properties of BL Lacs detected with the *EGRET* instrument on the *Compton Gamma-Ray Observatory* (Hartman et al. 1999), or otherwise found to emit high energy γ-rays, and their counterparts that were not detected by *EGRET* (Section 4). Our conclusions are summarized in Section 5.

Table 2. Positions and magnitudes of the comparison stars

IAU Name	Star	RA(2000)	DEC(2000)	B (mag)	R (mag)
0003+158	S1	00 06 08.42	+16 09 54.4	16.31	15.32
	S2	00 06 06.20	+16 10 46.3	17.17	15.71
	S3	00 06 05.97	+16 12 15.6	16.89	15.49
0025+307	S1	00 28 25.59	+31 03 19.0	15.57	14.11
	S2	00 28 15.86	+31 03 09.8	15.57	13.89
0043+039	S1	00 45 39.87	+04 10 02.0	16.95	15.50
	S2	00 45 44.87	+04 10 57.9	17.34	16.09
	S3	00 45 44.16	+04 13 26.0	17.76	15.21
0806+315	S1	08 09 06.08	+31 22 19.3	16.52	15.09
	S2	08 09 18.58	+31 22 20.7	16.54	15.11
	S3	08 09 14.89	+31 20 18.7	17.65	15.92
0824+098	S1	08 27 39.18	+09 41 13.5	16.60	15.03
	S2	08 27 44.30	+09 45 05.6	16.28	15.44
0832+251	S1	08 35 26.47	+24 57 12.2	18.86	16.62
	S3	08 35 47.24	+24 57 19.0	16.56	15.72
0846+513	S1	08 50 14.07	+51 06 21.9	17.27	16.11
	S3	08 50 19.88	+51 09 00.0	17.34	18.67
0850+440	S1	08 53 28.75	+43 46 22.8	18.37	16.08
	S2	08 53 48.92	+43 48 28.1	18.03	16.39
	S3	08 53 39.97	+43 46 15.4	18.72	16.46
0931+437	S1	09 34 46.90	+43 32 05.9	15.75	14.42
	S2	09 35 01.19	+43 27 43.4	15.72	15.24
0935+416	S1	09 38 40.37	+41 26 11.3	16.11	15.32
	S3	09 39 02.53	+41 30 37.9	16.27	15.47
0945+438	S1	09 49 28.88	+43 37 54.4	15.30	14.35
	S3	09 49 06.74	+43 29 08.2	17.18	15.27
	S4	09 48 58.30	+43 55 11.8	17.28	16.14
1029+329	S1	10 32 10.68	+32 36 08.1	16.37	15.02
	S2	10 32 07.49	+32 37 28.2	17.35	15.33
1418+546	S1	14 20 02.31	+54 25 25.3	16.28	15.58
	S2	14 19 46.29	+54 26 43.4	16.11	15.51
	S3	14 19 39.75	+54 21 56.1	16.74	15.44
1422+424	S1	14 25 03.56	+42 14 41.8	16.27	15.67
	S2	14 25 09.20	+42 17 21.8	18.14	16.81
	S3	14 25 11.09	+42 17 51.2	15.97	15.39
1425+267	S1	14 27 47.53	+26 35 14.9	15.21	13.65
	S2	14 27 30.07	+26 36 05.5	15.59	14.01
1444+407	S1	14 16 54.96	+40 36 51.9	15.68	14.10
	S2	14 46 55.62	+40 36 16.6	17.04	14.99
1522+101	S1	15 24 03.25	+09 58 15.2	16.99	15.03
	S2	15 24 07.32	+10 01 02.9	17.12	15.56
1553+113	S1	15 55 35.71	+11 09 33.2	16.11	15.11
	S3	15 55 51.81	+11 12 28.7	16.55	15.45
1631+395	S1	16 33 01.57	+39 20 49.4	17.20	15.90
	S3	16 32 54.19	+39 21 19.8	17.91	16.48
1750+507	S1	17 51 07.39	+50 45 03.5	20.11	19.55
	S2	17 51 06.32	+50 44 33.9	16.38	14.81
	S3	17 51 37.59	+50 43 56.5	15.70	14.80

2 INTRANIGHT OPTICAL MONITORING

All AGNs chosen for this additional study had to be bright enough to allow a high temporal density for precision differential photometry using telescopes of a modest aperture. This led to a requirement that $m_B < 17$ mag. We also wanted to minimize the contamination problems that arise when the host galaxy contributes a significant portion of the visible light (e.g. Cellone, Romero & Combi 2000), and so restricted our sample to luminous AGNs (quasars), with $M_B < -23.5$ mag. For good visibility from India the sources had to be at moderate positive declinations and within suitable ranges of right ascensions. Basic data on our sources is presented in Table 1. Twelve of the sources are RQQs (using the usual criterion for the K-corrected ratio of 5 GHz to 2500Å fluxes, $R^* < 10$), 4 are LDQs, 1 is a CDQ, and 3 are BLs; their redshifts range from 0.22 to 1.97.

The majority of the data was obtained at ARIES (formerly UPSO), Naini Tal, India, using the 104-cm Sampurnanand telescope which is an RC system with a f/13 beam (Sagar 1999). The detectors used were a cryogenically cooled

1024 × 1024 CCD chip (prior to October 1999) and a 2048 × 2048 chip (after October 1999), both mounted at the cassegrain focus. The 1k×1k chip has a readout noise of 7 electrons and a gain of 11.8 electrons/ADU, whereas the 2k×2k chip has a readout noise of 5 electrons (in the usually employed slow readout mode) and a gain of 10 electrons/ADU. Each pixel of both of these CCDs correspond to 0.38 × 0.38 arcsec^2 on the sky, covering a total field of $12' \times 12'$ in the case of the larger CCD and $6' \times 6'$ in the case of the smaller CCD (Sagar 1999). An R Cousins filter was used for these observations. On each night only one AGN was monitored, as continuously as possible. The choice of exposure times depended on the brightness of the object, the moon's phase, and sky transparency. The field containing the AGN was adjusted so as to have within the CCD frame at least 2 (usually 3 or more) comparison stars within about a magnitude of the AGN; for nearly all objects we were able to find at least one steady comparison star fainter, or $<$ 0.4 mag brighter, than the AGN, so as to obtain an equivalent S/N in the CCD frames. Seeing ranged from about 1.5 to about 3.5 arcsec.

Four of the RQQs in the sample were monitored in V Johnson passband using a cryogenically cooled Tektronix CCD detector at the f/3.23 prime focus of 2.34 meter Vainu Bappu Telescope (VBT) of the Indian Institute of Astrophysics, at Kavalur, India (Table 3). The chip has 1024 × 1024 pixels of approximately 24 × 24 μm^2, with each pixel dimension corresponding to about 0.63 arcsec on the sky, so that the total area covered by a CCD frame is $10.75' \times 10.75'$. The readout noise was 4 electrons and the gain was 4 electrons/ADU. Typical seeing was around 2 arcsec.

One night of monitoring data for the RQQ 1422+424 reported here was carried out in V Johnson passband using the Tektronix 1k×1k CCD detector at the f/13 Cassegrain focus of the 1.2 meter Gurushikhar Telescope (GSO) at Mount Abu, India (Table 3). Each pixel corresponds to 0.32 arcsec in each dimension and the entire chip covers approximately $5.4' \times 5.4'$ of sky. The readout noise was 4 electrons and gain was 10 electrons/ADU. Typical seeing was ∼1.5 arcsec.

At all three telescopes, observations were carried out in 2×2 binned mode, in order to increase S/N; bias frames were taken intermittently and twilight sky flats were taken for processing of the data. Initial processing (bias subtraction, flat-fielding and cosmic ray removal) as well as photometric reductions was done in the usual manner employing standard routines in IRAF[1] software.

Instrumental magnitudes of the AGN and the stars in the images taken at Naini Tal were obtained using the routines available in the *apphot* package in IRAF. For these reductions, a crucial parameter, the circular aperture used for the photometry of the QSO and the comparison stars, varied from night to night. For each night an optimum aperture for the photometry was selected by considering a range of apertures starting from a minimum corresponding to the median seeing (FWHM) over the night; we chose the aperture that produced the minimum variance in the star−star differential light curve (DLC) of the steadiest pair of comparison stars. Additional details of the observation and reduction procedures are presented elsewhere (Stalin 2003; St04b).

Instrumental magnitudes of the AGN and stars in the image frames acquired at VBT and GSO were determined by using DAOPHOT II[2] (Stetson 1987) and employing aperture photometric techniques. The best S/N was found for data reduced with a 7.0 pixel radius and it is thus used for our analysis.

The positions and the B and R magnitudes (taken from the USNO-B catalog[3] (Monet et al. 2003) for the comparison stars used in our analysis are given in Table 2. Note that the magnitudes of the comparison stars taken from this catalog have uncertainties of up to 0.25 mag, though errors for individual objects are not provided.

3 RESULTS OF INTRA-NIGHT MONITORING

Figure 1 presents the DLCs for all the nights on which significant variability was detected for any AGN in the present sample. It can be seen that in these data, variability of the order of 0.01 mag over the course of a few hours can be detected. A log of the observations and the main results are given in Table 3. For each night of observations of every object, this table provides the number of data points (Npoints), the duration, an indicator of the variability status, as well as two quantitative measures of the variability, $C_{\rm eff}$ and ψ (see below).

The parameter $C_{\rm eff}$ is defined, basically following Jang & Miller (1997), for a given DLC as the ratio of the standard deviation of all its data points, σ_T, to the averaged standard deviation for its individual data points, $\sigma = \eta\sigma_{\rm err}$. Here η is the factor by which the average of the measurement errors ($\sigma_{\rm err}$, as given by *phot*) should be multiplied; we find $\eta = 1.50$ (Stalin 2003; St04b). We compute $C_{\rm eff}$ from the C_i values (defined as the ratio of the standard deviation of i^{th} DLC to the mean σ of its individual data points multiplied by the factor η) determined for the DLCs of an AGN relative to different comparison stars, measured on a single night (see Sa04 for details). A value of $C_{\rm eff} > 2.57$ corresponds to a confidence level of variability in excess of 0.99 and is the criterion we use to assign variability to a QSO. We note that for these AGN all the DLCs involving only their comparison stars were found to show statistically insignificant variability, using the same statistical criterion.

We quantify the actual variation of the QSO on a given night using the error corrected amplitude of variability, ψ, as defined by Romero, Cellone & Combi (1999),

$$\psi = \sqrt{(D_{max} - D_{min})^2 - 2\sigma^2}, \qquad (1)$$

with D_{max} (D_{min}) the maximum (minimum) in the quasar DLC, and σ the corrected error value described in the previous paragraph. Details are given in St04b.

The structure function (SF) is frequently used to characterize variability properties such as time-scales and periodicities present in the light-curves. We have also computed the SFs for our dataset in the fashion discussed in some detail in Sa04 and St04b. Basically, a monotonically rising

[1] Image Reduction and Analysis Facility, distributed by NOAO, operated by AURA, Inc. under agreement with the US NSF.

[2] Dominion Astrophysical Observatory Photometry Software

[3] http://www.nofs.navy.mil/data/fchpix

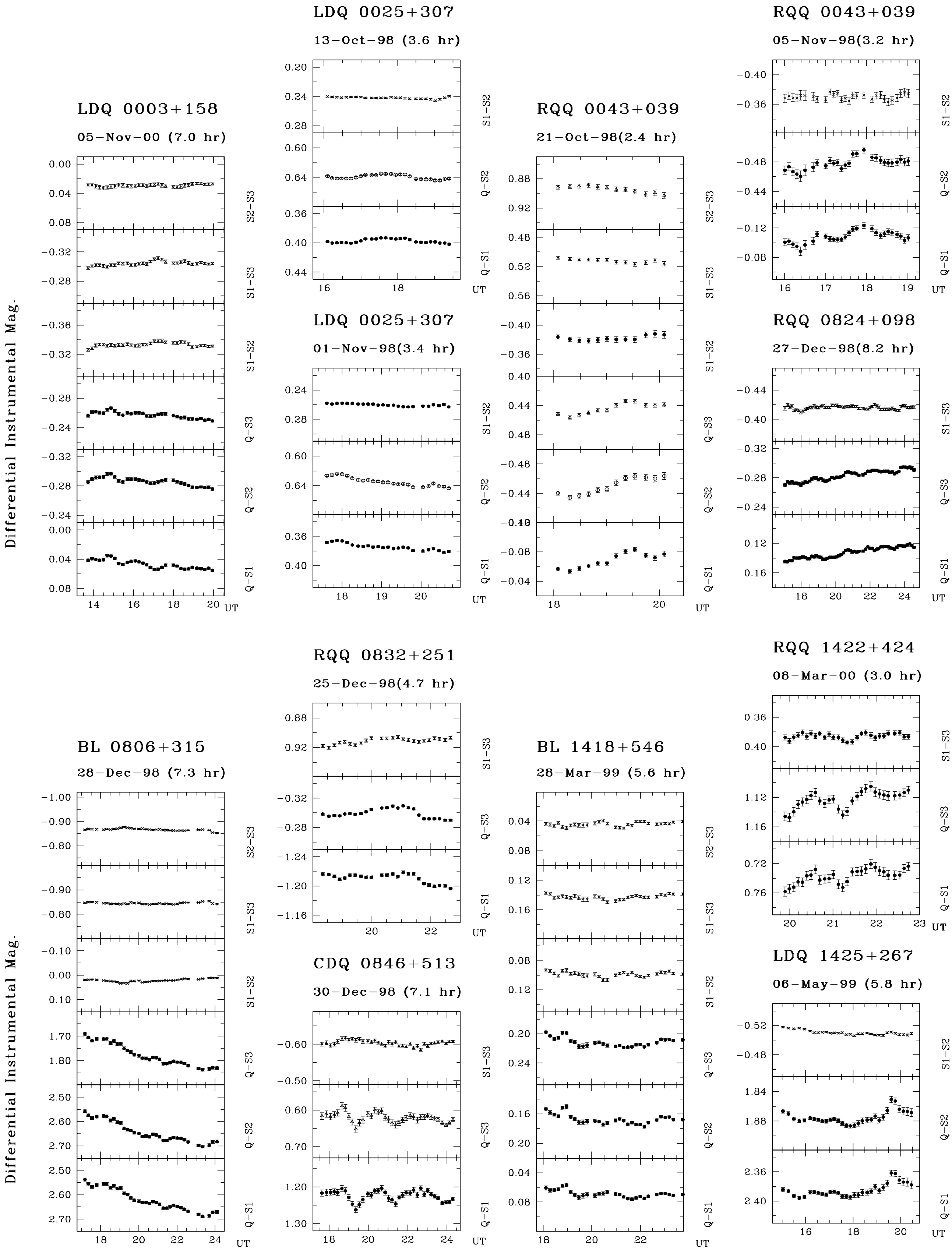

Figure 1. Differential light curves (DLCs) for the quasars on nights with a positive detection of INOV. The name of the quasar, the date, and the duration of the observation are given at the top of each night's data. The upper panel(s) give the DLCs for the various pairs of comparison stars available and the subsequent panels give the quasar-star DLCs, as defined in the labels on the right side.

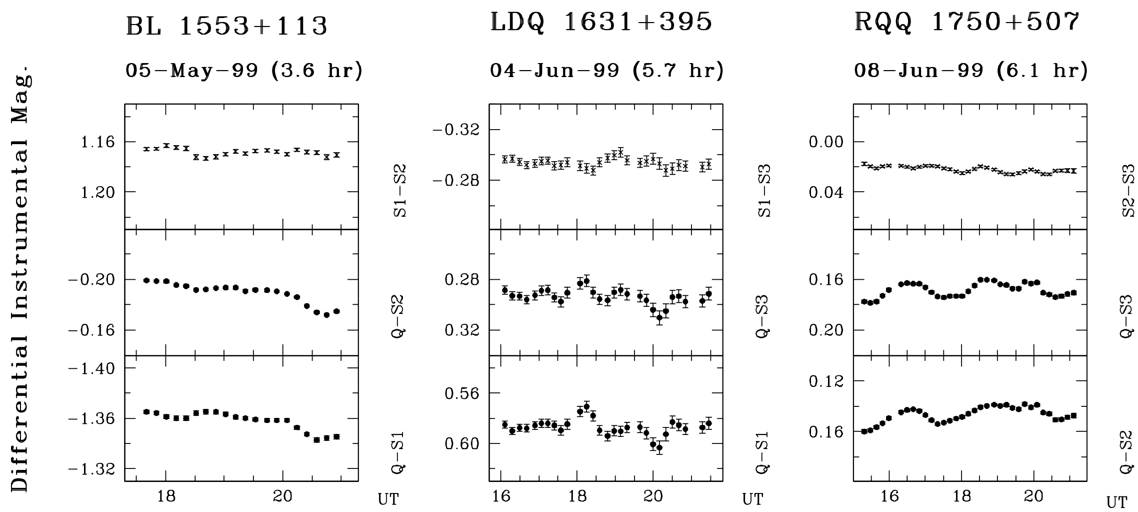

Figure 1. *Continued*

Table 3. Observation log and variability results

IAU Name	Other Name	Type	Date	Filter	Telescope	Npoints	Duration (hours)	Status*	$C_{\rm eff}$	ψ (%)
0003+158	PKS	LDQ	03.11.00	R	ARIES	28	5.8	NV	—	—
			05.11.00	R	ARIES	32	7.0	V	3.1	1.8
0025+307	RXS	LDQ	13.10.98	R	ARIES	26	3.6	V	2.7	0.8
			01.11.98	R	ARIES	24	3.4	V	5.1	1.9
0043+039	PG	RQQ	21.10.98	R	ARIES	12	2.4	V	4.2	2.5
			05.11.98	R	ARIES	28	3.2	V	2.6	3.2
0806+315	B2	BL	28.12.98	R	ARIES	34	7.3	V	> 6.6	14.5
0824+098	1WGA	RQQ	27.12.98	R	ARIES	58	8.2	V	4.3	2.2
0832+251	PG	RQQ	25.12.98	R	ARIES	24	4.7	V	4.3	2.0
			14.01.99	R	ARIES	63	7.3	NV	—	—
			10.12.99	R	ARIES	31	6.7	NV	—	—
0846+513	0846+51	CDQ	30.12.98	R	ARIES	37	7.1	V	2.8	5.6
0850+440	US 1867	RQQ	17.02.99	R	ARIES	37	7.7	NV	—	—
0931+437	US 737	RQQ	20.02.99	R	ARIES	24	4.5	NV	—	—
0935+416	PG	RQQ	27.03.99	R	ARIES	15	2.7	NV	—	—
0945+438	US 995	RQQ	15.01.99	V	VBT	10	2.2	NV	—	—
1029+329	CSO 50	RQQ	13.03.99	V	VBT	57	5.4	NV	—	—
1418+546	OQ 530	BL	28.03.99	R	ARIES	31	5.6	V	4.0	2.0
1422+424	RXS	RQQ	03.04.99	R	ARIES	39	7.2	NV	—	—
			14.04.99	V	VBT	40	4.1	NV	—	—
			07.03.00	R	ARIES	15	3.9	NV	—	—
			08.03.00	V	GSO	28	3.0	V	2.9	3.6
1425+267	B2	LDQ	06.05.99	R	ARIES	31	5.8	V	2.8	3.2
1444+407	PG	RQQ	15.04.99	V	VBT	28	2.9	NV	—	—
1522+101	PG	RQQ	11.04.99	R	ARIES	36	6.6	NV	—	—
1553+113	PG	BL	05.05.99	R	ARIES	20	3.6	V	>6.6	2.3
			06.06.99	R	ARIES	40	7.1	NV	—	—
1631+395	KUV	LDQ	04.06.99	R	ARIES	28	5.7	V	2.9	2.7
			30.05.00	R	ARIES	12	3.5	NV	—	—
1750+507	IRAS	RQQ	03.06.98	R	ARIES	44	4.7	NV	—	—
			06.06.98	R	ARIES	15	1.6	NV	—	—
			08.06.99	R	ARIES	34	6.1	V	>6.6	2.0

*V = variable; NV = non-variable

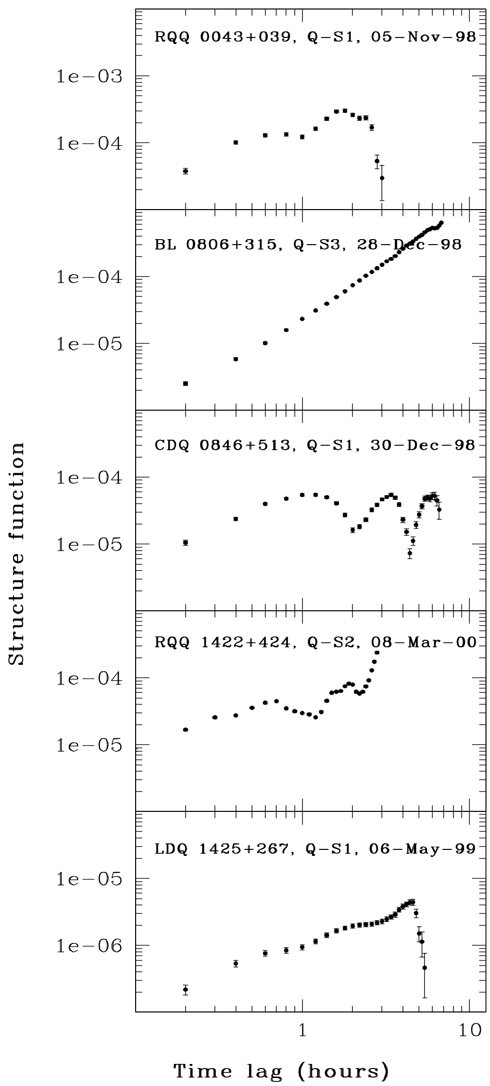

Figure 2. Structure functions for the 5 most strongly variable quasar light curves. The object, DLC descriptor and date label each of the panels.

SF indicates that the source shows no temporal structure on time scales shorter than the duration of the light curve, while the beginning of a plateau in the SF signifies a time-scale for the variability and a dip in the SF may be indicative of a periodic component. Figure 2 shows the SFs for five objects on the nights when they were rather strongly variable, with $\psi > 0.03$ mag.

We now give brief comments on a few of the sources that showed INOV.

RQQ 0043+035 varied on both the nights it was observed; on the first night it brightened by ~ 0.02 mag in ~ 1 hour. On the second night, about 2 weeks later, the data were relatively noisy; nonetheless, a brightening by about ~ 0.03 mag over 2 hours is clearly detected. The structure function for this night shows a time scale of roughly 1.5 hours (Fig. 2).

BL 0806+315: on the single night this BL Lac was monitored for about 7 hours, a fading by about 0.15 mag was detected. The SF indicates that no time scale shorter than the monitoring duration is present (Fig. 2).

CDQ 0846+513 is the only core-dominated quasar in the present sample. A fluctuation of ~ 0.05 mag can be seen on its DLC. The SF shows hints of periodicities of about 2 and 4.5 hours (Fig. 2); but the data train is much too short to justify claiming them as actual periodicities. As this is a gravitationally lensed quasar (e.g. Maoz et al. 1993), much of its variability may be extrinsic, produced by microlensing.

RQQ 1422+424 showed variability on just one of the 4 nights it was monitored. The DLC in Fig. 1 shows a quasi-oscillatory pattern, with an amplitude of ~ 0.04 mag. The SF suggests a timescale of ~ 1 hour (Fig. 2).

LDQ 1425+267 showed a weak flare of ~ 0.02 mag near 19.6 UT on the single night it was monitored. The SF hints at a time scale of ~ 4 hours (Fig. 2).

In order to obtain more significant estimates of the INOV duty cycle (DC), we have combined the results for the 12 RQQs, 4 LDQs and 3 BLs in this sample with the extensive monitoring data presented for these AGN classes in our earlier work (St04a, Sa04). It may be recalled that for a given class of objects, the DC is defined as the weighted fraction of its DLCs which show INOV, where the contribution of an individual DLC to this fraction is weighted inversely by the duration of that DLC in the emitter's frame (Romero et al. 1999; GK03; St04a,b; Sa04). Using these enlarged samples based on our observations, we estimate DCs of 22 per cent, 22 per cent, and 63 per cent for RQQs, LDQs, and BLs, respectively.

4 STATISTICS OF INOV IN BL LACS USING ENLARGED DATASETS

Although INOV of blazars has been clearly established for about 15 years (Miller et al. 1989; Carini 1990), only recently has enough data been accumulated to allow a reliable description of its frequency and amplitude, and to examine if various AGN classes exhibit different INOV behaviour. In order to increase the sample of light curves (LCs) we have combined the results for BLs in this paper with those reported in Sa04 and in other papers taken from the literature from 1990 through 2003 reporting intra-night optical monitoring of BLs (as classified in the Véron-Cetty & Véron catalogue, 2001). Note that the object 0537−441 may also be classified as a CDQ (see Maraschi et al. 1985); however, we have considered it to be a BL in our analysis. While it is possible that our literature search is less than complete, we believe that our selection of BL Lac monitoring data is both extensive and representative. We have not included in our sample data from papers where results are presented for just a single BL Lac object, nor where the duration of the LC is shorter than 4 hours. These criteria led to the selection of 51 LCs with durations ranging between 4 and 10 hours (median = 6.5 hours). These LCs correspond to 12 BLs, (Table 4) reported in 4 papers: present work (3 LCs, R-filter); Sagar et al. 2004 (26 LCs, R-filter); Romero et al. 2002 (19 LCs, V-filter); Ghosh et al. 2001 (3 LCs, B-filter). For the present purpose, we do not distinguish between data taken using the different filters. It may be noted that the rms error of individual data points is typically $\sim$0.003 mag for all the 51 LCs considered.

Table 4. Consolidated list of the BL Lacs in the extended sample

IAU name	m_B	M_B	z	P^*_{opt} (%)	log R*†	EGRET‡
0219+428	15.71	−26.5	0.444	11.7	2.8	Yes
0235+164	16.46	−27.6	0.940	14.9	3.4	Yes
0414+009	16.86	−24.6	0.278	2.8	2.2	No
0537−441	17.00	−27.0	0.894	10.5	3.8	Yes
0735+178	16.76	−25.4	>0.424	14.1	3.5	Yes
0806+315	15.70	−25.0	0.220	—	1.7	No
0851+202	15.91	−25.5	0.306	12.5	3.3	Yes
1215+303	16.07	−24.8	0.237	8.0	2.6	No
1308+326	15.61	−28.6	0.997	10.2	2.8	No
1418+546	16.17	−23.7	0.151	7.5	3.1	No
1553+113	15.00	−26.8	0.360	—	2.2	No
2155−304	13.36	−25.9	0.116	4.9	1.5	TeV

*References for optical polarizations: Wills et al. 1992; Impey & Tapia 1988; Marcha et al. 1996; — implies no data available
†R^* is the K-corrected ratio of the 5 GHz radio to 2500 Å-band optical flux densities (Stocke et al. 1992); reference for radio fluxes: Véron-Cetty & Véron 2001
‡Reference for EGRET detections: Hartman et al. 1999; for TeV detection: Chadwick et al. 1999

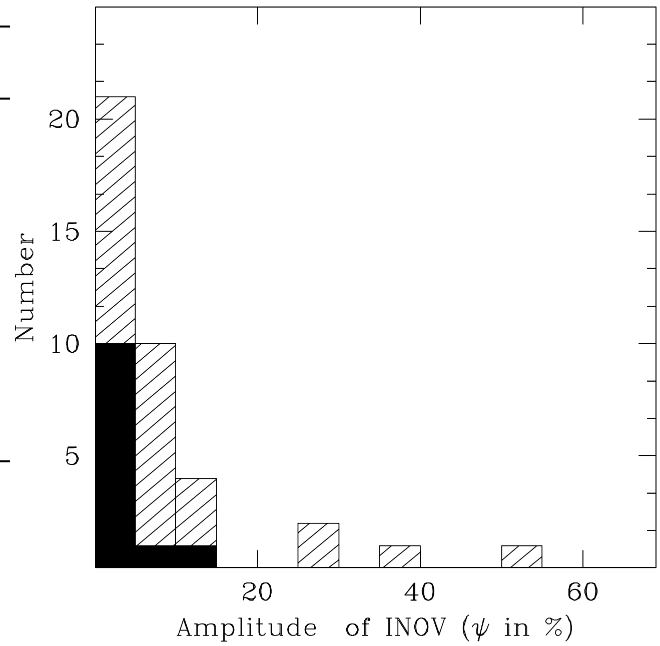

Figure 3. Distributions of INOV amplitude (ψ), for 39 light-curves of the 6 EGRET (hatched) and 12 light-curves of the 6 non-EGRET (black) BLs.

In Fig. 3 we present the distributions of the INOV amplitude, ψ, for two subsets of the 51 (high quality) LCs. These subsets are derived by applying the criterion whether or not the LC refers to a BL detected in γ–rays with EGRET (Hartman et al. 1999), and/or at TeV energies (Chadwick et al. 1999). Henceforth, such BLs will be referred to by the common name EGRET-BLs. Likewise, BLs not detected at γ-ray energies will be called non-EGRET-BLs. A Kolmogorov–Smirnov (K-S) test performed on the two ψ distributions rejects the null hypothesis that the two distributions are identical; its probability in only 0.038. Thus, EGRET BL Lacs appear to show stronger INOV as compared to non-EGRET BL Lacs, though both the number of nights of observations per object and the total number of objects is too small to allow this to be a firm conclusion at this stage. If confirmed using larger samples, this would suggest a stronger Doppler beaming for EGRET BL Lacs. Possible physical scenarios for this difference are mentioned in Sect. 5.

5 CONCLUSIONS

We have presented new observations of intra-night optical monitoring for 20 powerful AGN, including 3 BL Lacs, 5 radio-loud quasars (RLQs) and 12 radio-quiet quasars (RQQs). INOV is detected in all three classes of AGN, consistent with the results reported in our earlier papers (GK03; St04a,b; Sa04). By combining the present data with the observations reported in our earlier papers (GK03; St04a; Sa04), we could assemble a larger AGN sample consisting of 19 RQQs, 9 BL Lacs and 16 RLQs (after excluding the high optical polarization quasar 1216−010 from the radio core-dominated RLQs in our sample).

The INOV duty cycles (DCs) derived for this sample are: 63% for BL Lacs, 18% for RLQs and 22% for RQQs. Thus, the INOV duty cycles for both RQQs and RLQs (5 of which are CDQs) are similar, and much smaller than that for BL Lacs. This supports our earlier result that the mere presence of a powerful radio synchrotron jet does not lead to an enhanced INOV (GK03; St04a). The observed similarity in the INOV of RQQs and non-blazar RLQs, both in terms of DC and ψ, further suggests that the RQQs also eject relativistic jets. Their jets are, however, probably quenched while crossing the innermost micro-arcsecond scale, possibly through heavy inverse Compton losses in the vicinity of the central engine (GK03). A similar conclusion has also been reported recently from radio variability studies of RLQs and RQQs (Barvainis et al. 2004).

Further, we have formed an enlarged sample of BL Lac objects with intra-night monitoring duration > 4 hours, by combining the 3 LCs reported here with 48 taken from the literature (Sect. 4). The duty cycle of INOV for this entire sample of 51 LCs of BL Lacs is found to be 68%.

Dividing this sample of 51 LCs by the criterion of detection of γ−rays (Table 4), we find that the γ−ray detected BLs show somewhat stronger INOV, the formal confidence being 0.962 using K-S test (Fig. 3). It is tempting to speculate about the possible origin of this difference. The synchrotron self-Compton (SSC) model for the origin of γ−rays posits that the γ−rays are produced by inverse Compton (IC) scattering of the synchrotron photons themselves off the relativistic jet electrons (e.g. Maraschi, Ghisellini & Celloti 1992; Bloom & Marscher 1996). The external Compton (EC) models invoke IC scattering of photons originating outside the jet, typically from the accretion disk around the central black hole (e.g. Dermer, Schlickeiser & Mastichiadis 1992), or disk photons reprocessed by matter above the disk but outside the jet (e.g. Sikora, Begelman & Rees 1994; Blandford & Levinson 1995). A variant of the EC model, the "mirror model", utilizes jet photons reflected or reprocessed by clouds external to the jet (Ghisellini & Madau 1996).

In the IC scenario involving external seed photons for γ–ray loud blazars, one expects the emission cone to be particularly sharp (Dermer 1995), raising the likelihood of detecting stronger and more rapid INOV (GK03). Hence, our current preliminary results provide additional support to the EC model. Nonetheless, more extensive, multi-band intranight monitoring observations of blazars are clearly needed. For the non-blazar AGN, the amplitude of INOV continues to be found to be small ($< 3\%$), emphasizing the need for even more sensitive monitoring programs.

ACKNOWLEDGEMENTS

It is a pleasure to thank Amy Campbell, Dick Miller and Angela Osterman for helpful conversations, and the referee for useful suggestions. CSS is grateful for hospitality at Georgia State University. GK would like to thank the Institute d'Astrophysique (Paris) for hospitality during this work. PJW is grateful for hospitality at Princeton University Observatory while this paper was written. PJW's efforts are partially supported by RPE funds to PEGA at GSU.

REFERENCES

Barvainis R., Léhar J., Birkinshaw M., Falcke H., Blundell K. M., 2004, astro-ph/0409554
Bauer F. E., Condon J. J., Thuan T. X., Broderick J. J., 2000, ApJS, 129, 547
Becker R. H., White R. L., Helfand D. J., 1995, ApJ, 450, 559
Berriman G., Schmidt G. D., West S. C., Stockman H. S., 1990, ApJS, 74, 869
Blandford R. D., Levinson A., 1995, ApJ, 441, 79
Bloom S. D., Marscher A. P., 1996, ApJ, 461, 657
Carini M. T., 1990, PhD thesis, Georgia State Univ.
Cellone S. A., Romero G. E., Combi J. A., 2000, ApJ, 119, 1534
Chadwick P. M. et al., 1999, ApJ, 513, 161
Condon J. J. et al., 1998, AJ, 115, 1693
Dermer C. D., 1995, ApJ, 446, L63
Dermer C. D., Schlickeiser R., Mastichiadis A., 1992, A&A, 256, L27
Ghisellini G. Madau P., 1996, MNRAS, 280, 67
Ghosh K. K., Kim C., Ramsey B. D., Soundarajaperumal S., 2001, J. Korean Astr. Soc., 34, 9
Gopal-Krishna, Sagar R., Wiita P. J., 1995, MNRAS, 274, 701
Gopal-Krishna, Gupta, A. C., Sagar R., Wiita P. J., Chaubey, U. S., Stalin, C. S., 2000, MNRAS, 314, 815
Gopal-Krishna, Stalin C. S., Sagar R., Wiita P. J., 2003, ApJ, 586, L25 (GK03)
Hartman R. C. et al., 1999, ApJS, 123, 79
Howard E. S., Webb J. R., Pollock J. T., Stencel R. E., 2004, AJ, 127, 17
Impey C. D., Tapia S., 1988, ApJ, 333, 666
Jang M., Miller H.R., 1997, AJ, 114, 565
Maoz D., Bahcall J. H., Doxsey R., Schneider D. P., Bahcall N. A., Lahav O., Yanny B. 1993, ApJ, 402, 69
Maraschi L., Ghisellini G., Celloti A., 1992, ApJ, 397, L5
Maraschi L., Schwartz D. A., Tanzi E. G., Treves A., 1985, ApJ, 294, 615
Marcha M. J. M., Browne I. W. A., Impey C. D., Smith P. S., 1996, MNRAS, 281, 425
Miller H. R., Carini M. T., Goodrich B. D., 1989, Nature, 337, 627
Monet D. G., et al., 2003, AJ, 125, 984
Romero G. E., Cellone S. A., Combi J. A., 1999, A&AS, 135, 477
Romero G. E., Cellone S. A., Combi J. A., Andruchow I., 2002, A&A, 390, 431
Sagar R., 1999, Current Science, 77, 643
Sagar R., Gopal-Krishna, Wiita P. J., 1996, MNRAS, 281, 1267
Sagar R., Stalin C. S., Gopal-Krishna, Wiita P. J., 2004, MNRAS, 348, 176 (Sa04)
Sikora M., Begelman M. C., Rees M. J., 1994, ApJ, 421, 153
Stalin C. S., 2003, PhD thesis, Kumaun Univ.
Stalin C. S., Gopal-Krishna, Sagar R., Wiita P. J., 2004a, MNRAS, 350, 175 (St04a)
Stalin C. S., Gopal-Krishna, Sagar R., Wiita P. J., 2004b, JA&A, 25, 1 (St04b)
Stetson P. B., 1987, PASP, 99, 191
Stocke J. T., Morris S. L., Weymann R. J., Foltz C. B., 1992, ApJ, 396, 487
Véron-Cetty M.-P., Véron P., 2001, A&A, 374, 92
Wagner S., Witzel, A., ARA&A, 33, 163
Wills B. J., 1996, in Kundt, W., ed, Jets from Stars and Galactic Nuclei, Springer-Verlag, Berlin, p. 213
Wills B. J., Wills D., Breger M., Antonucci R. R. J., Barvainis R., 1992, ApJ, 398, 454