

Intranight optical variability of radio-quiet and radio lobe dominated quasars

C. S. Stalin^{1,2*}, Gopal-Krishna¹, Ram Sagar², and Paul J. Wiita³

¹*National Centre for Radio Astrophysics, TIFR, Pune University Campus, Post Bag No. 3, Ganeshkhind, Pune 411007, India*

²*State Observatory, Naini Tal, 263129, India*

³*Department of Physics & Astronomy, MSC 8R0314, Georgia State University, Atlanta, Georgia 30303-3088, USA*

Accepted 2003 March xxx. Received 2003 March xxxx

ABSTRACT

We present results of a programme of multi-epoch, intra-night optical monitoring of a sample of non-blazar type AGN, which includes seven radio-quiet QSOs (RQQs) and an equal number of radio-loud, lobe-dominated quasars (LDQs), covering a redshift range from about 0.2 to 2.0. These two sets of optically bright and intrinsically luminous QSOs are well matched in the redshift–optical luminosity ($z - M_B$) plane. Our CCD monitoring covered a total of 61 nights with an average of 6.1 hours of densely sampled monitoring of just a single QSO per night, thereby achieving a typical detection threshold of $\sim 1\%$ variation over the night. Unambiguous detection of intra-night variability (INOV) amplitudes in the range 1–3% on day-like or shorter time scales were thus made for both RQQs and LDQs. Based on these clear detections of INOV, we estimate duty cycles of 17% and 9% for RQQs and LDQs, respectively; inclusion of the two cases of probable variations of LDQs would raise the duty cycle to 15% for LDQs. The similarity in the duty cycle and amplitude of INOV for the RQQs and LDQs suggests, firstly, that the radio loudness alone does not guarantee an enhanced INOV in QSOs and, secondly, that as in LDQs, relativistic jets may also be present in RQQs. We argue that, as compared to BL Lacs, the conspicuously milder, rarer and possibly slower INOV of RQQs and LDQs, can in fact be readily understood in terms of their having optical synchrotron jets which are modestly misaligned from us, but are otherwise intrinsically as relativistic and active as the jets in BL Lacs. This points toward an orientation-based unifying scheme for the INOV of radio-loud and radio-quiet quasars. Variability of up to ~ 0.3 -mag on month to year-like time scales is seen for nearly all those RQQs and LDQs in our sample for which sufficient temporal coverage is available. These data have revealed an interesting event that seems most likely explained as an occultation, lasting less than six months, of much of the nuclear optical continuum source in an RQQ. The observations reported here form part of a larger ongoing project to study the intra-night optical variability of four major classes of powerful AGN, including blazars.

Key words: galaxies: active — galaxies: jets — galaxies: photometry — quasars: general

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; Carini et al. 1991), though its origin and

relation to longer term variability remains unclear (e.g. Wiita 1996). 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 1990; Wagner & Witzel 1995). Intranight variability in blazars may well arise from instabilities or fluctuations

in the flow of such jets (e.g. Hughes, Aller & Aller 1990; 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 (Sopp & Alexander 1991; Terlevich et al. 1992; also see Antonucci, Barvainis & Alloin 1990). This finds support from the observed strong correlation between γ -ray detection (using EGRET) and radio loudness (e.g. Bregman 1994; see Gopal-Krishna, Sagar & Wiita 1995). In this case, accretion disk instabilities may be responsible for any rapid fluctuations detected in RQQs (e.g. Zhang & Bao 1991; 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; Papadopoulos et al. 1995; Kukula et al. 1998; Blundell & Beasley 1998; Blundell & Rawlings 2001). The existence of incipient nuclear jets in RQQs has also been inferred by Falcke, Patnaik & Sherwood (1996), from radio spectral measurements of optically selected quasar samples. The recent clear detection of intra-night optical variability (INOV) of a few *bona-fide* RQQs is readily explained in terms of relativistic jets on the optically emitting length scales (Gopal-Krishna et al. 2003; hereafter GSSW03).

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. A similar conclusion has been reached in a recent analysis of the radio properties of the 2dF QSO redshift survey (Cirasuolo et al. 2003), employing the FIRST radio survey (Becker, White & Helfand 1995). 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 the RL/RQ dichotomy, some of them based on the idea that more rapidly spinning black holes produce powerful relativistic jets (e.g. Blandford 2000; Wilson & Colbert 1995). Others models argue that the radio emission correlates with the mass of the nuclear black hole (e.g. Dunlop et al. 2003); however, this assertion has been questioned (Ho 2002; Woo & Urry 2002). Yet other models stress the importance of accretion rate and possible changes in accretion mode to this dichotomy (e.g. McLure & Dunlop 2001).

We have been pursuing the question INOV in RQQs for a decade now, expecting that any intrinsic differences between the central engines of RL and RQ classes of AGN could be reflected in their short-term optical variability. We have carried out CCD monitoring of over a dozen optically luminous, bright RQQs, beginning with the first such attempt to do so reported in Gopal-Krishna, Wiita & Altieri (1993). Our subsequent work used the 2.34m Vainu Bappu

telescope of the Indian Institute of Astrophysics, Bangalore; later the 1.04m Sampurnanand telescope of the State Observatory, Naini Tal, was increasingly employed (Gopal-Krishna, Sagar & Wiita 1993, 1995, hereafter Papers I and II, respectively; Sagar, Gopal-Krishna & Wiita 1996, Paper III; Gopal-Krishna et al. 2000, Paper IV). While we found several reasonably persuasive incidences of INOV for some RQQs, it was clearly necessary to extend this study through a more sensitive and systematic programme to confirm and better characterize this phenomenon.

This endeavour involved an optical monitoring campaign lasting 113 nights from November 1998 through May 2002 of a matched sample (in both apparent magnitude and redshift) of radio-quiet and several classes of radio-loud quasars (BL Lacertae objects, BL; core dominated quasars, CDQs; and lobe dominated quasars, LDQs). Here we present our key results on the nature of INOV for the non-blazar subset comprised of seven RQQs and seven LDQs. A brief report on some of these results has been published recently (GSSW03). In a forthcoming paper we shall be reporting results for the BL Lac and CDQ components of this program (Sagar et al. 2003). Additional details can be found in Stalin (2002) and Stalin et al (2003).

2 CURRENT STATUS OF INOV IN RQQS

In Papers III and IV, where a fairly dense temporal sampling was achieved, we reported several instances of apparently significant INOV for RQQs. These events could be classified as small gradual variations lasting over several hours (e.g. 1630+377), time resolved microvariability on hour-like timescales (e.g. 0946+301, 1444+407), and single-point fluctuations, designated as “spikes” (e.g. 0748+294, 0824+098, 1444+407, 1630+377).

Other groups also have made attempts to detect and characterize INOV among radio quiet AGN (Petrucci et al. 1999; Rabbette et al. 1998) and among mixed samples of RQ and RL AGN (Jang & Miller 1995, 1997; de Diego et al. 1998; Rabbette et al. 1998; Romero, Cellone & Combi 1999). Even if the variations claimed in these works were correctly identified, it appeared that both the INOV amplitude and the duty cycle of the RQQs were small compared to those found in many studies of blazars (e.g. Carini et al. 1992; Heidt & Wagner 1998; Xie et al. 2002; Romero et al. 2002).

Among the other studies of RQ AGN variability, that of Petrucci et al. (1999) exclusively involved Seyfert 1 galaxies, which are much weaker than the sources we consider here. Because the AGN contribution to the total light is minor, seeing variations can greatly complicate accurate detections of variations in the nuclei of Seyferts. The programme of Rabbette et al. (1998) involved BVR monitoring of 23 high luminosity RQQs, 22 of which are at $z > 1$. While the basic approach of using 2–3 comparison stars within the CCD frame, as well as keeping the exposure time at around 10 minutes, are similar to the present work, there are major differences as well. Firstly, in the program of Rabbette et al. (1998), intra-night sampling was usually much sparser, with only a few data points per object per night. This, coupled with their typical rms noise of 4% raises their microvariability detection threshold to ~ 0.1 mag, which is many times higher than that attained in our observations. The same

large errors also hamper their attempts to detect longer-term variability. We believe that this factor can explain their total lack of detection of intra-night variations and the near absence of night-to-night or longer-term variability in their observations of RQQs. Thus, given the differences in their observational approach and instrumental sensitivity, the results of the two campaigns are not discrepant.

Over the past several years a number of independent studies have been carried out to investigate the difference between the INOV in RL and RQ AGNs, with the goal of constraining models of the RL/RQ dichotomy. Jang & Miller (1995, 1997) studied a total sample of 19 RQ AGN and 11 RL AGN and found INOV in 3 (16%) of the former and 9 (82%) of the latter. However, optical luminosities of these RQ AGNs are modest, $M_B > -24.3$, and close to the critical value below which the radio properties are thought to become like those of Seyfert galaxies (Miller, Peacock & Mead 1990); hence they are not the *bona-fide* quasars which are our primary concern here.

Romero et al. (1999) monitored a sample of 23 southern quasars: 8 RQQs and 15 blazars. The details of the production of their differential light curves differed somewhat from those of Papers I–IV and of Jang & Miller (1995, 1997), particularly in their averaging of 6 comparison stars to produce two effective comparison objects. Still, this approach should provide basically very similar results unless one or more of their comparison stars also showed substantial INOV, in which case their stellar errors will be too large and their detection threshold for AGN variability will be too high. None of their 8 RQQs was found to vary down to 1% rms, while 9 of the 15 blazars showed INOV. Romero et al. (1999) enlarged their above-mentioned sample by including the objects monitored by us in Paper II and by Jang & Miller (1995, 1997). This enlarged sample contained 27 RQQs and 26 RLQs and they derived duty cycles for the RLQs and RQQs of above 70% and only 3%, respectively, from this mixed sample. Here “duty-cycle” is defined as the ratio of the observational sessions during which objects of the particular class are detected as variable to the total observing time spent on objects in that class.

In contrast to the results summarized so far, de Diego et al. (1998) concluded that microvariability is as at least as common among RQQs as it is among the (relativistically beamed) CDQ sources, commonly deemed as blazars. They claimed detections of INOV in 6 of 30 RQQ monitoring sessions and only 5 of 30 CDQ sessions. Their sample was chosen so that each of their 17 RQQs had a CDQ counterpart of nearly matching brightness and redshift. However, their study differs radically from all other programs, including ours, in the procedure adopted for observation and analysis. de Diego et al. (1998) observed each source only between 3 and 9 times per night; each such observation consisted of five 1-minute exposures of the target field. An INOV analysis was then made through an ANOVA procedure which attempts to determine observational errors directly from the scatter in the object minus a reference star for the 5 points within each set of observations. The other programs, on the other hand, obtained degree of significance of variations either from the errors given by an aperture photometry algorithm, after suitable calibration, or from the scatter in the differential light curves (DLCs) of the comparison stars; we believe these techniques to be more reliable.

These markedly discrepant recent results prompted us to pursue this question by conducting an extensive programme of sensitive intra-night monitoring of a large sample of powerful AGN representing the four major classes mentioned above.

3 OBSERVATIONS

3.1 The sample and instruments used

The sample of non-blazar objects (i.e. RQQs and LDQs) considered in this paper consists of seven pairs of these AGN covering a total redshift range from 0.17 to 1.92 (Table 1), taken from the catalog of Véron-Cetty & Véron (1998). Each pair is closely matched in both z and B magnitude: their catalogued apparent magnitudes are $15 < m_B < 17$ and their absolute magnitudes range between -24.3 and -29.8 (assuming $H_0 = 50$, $q_0 = 0$), so all of these objects are *bona fide* QSOs. The radio properties of RQQs were determined from Kellermann et al. (1994), supplemented by the NVSS (Condon et al. 1998) and FIRST (Becker, White & Helfand 1995) surveys at 1.4 GHz, and our own VLA observations of two of the RQQs at 5 GHz (1029+329 and 1252+020). For all the seven RQQs, $R < 1$, where R is the rest-frame ratio of 5 GHz to 250 nm flux densities, computed following the prescription of Stocke et al. (1992). The criteria adopted for an LDQ designation was a radio spectral index $\alpha < -0.5$ ($S_\nu \propto \nu^\alpha$) as determined either from simultaneous flux measurements between 1 – 22 GHz (Kovalev et al. 1992) or from NED[†]. For five of the seven LDQs sufficiently detailed radio maps are available, and the core emission at 5 GHz is found to be weaker than the lobe emission (see Wills & Browne 1986). Evidence for lack of strong beamed non-thermal emission in the optical continuum is the weak optical polarization ($< 1.5\%$) known for five of the seven LDQs in our sample (Wills et al. 1992). Additional details concerning the sample selection, including our VLA observations and also the results for the blazar component of our programme, can be found in Sagar et al. (2003), Stalin (2002) and Stalin et al. (2003).

All observations reported here were carried out at the State Observatory, Naini Tal, using the 104-cm Sampurnanand telescope; this is an RC Cassegrain system with a f/13 beam (Sagar 1999). The detector used for the observations was a cryogenically cooled 2048×2048 Wright CCD, except prior to October 1999, when a 1024×1024 Tektronix CCD was in use. In each CCD a pixel corresponds to $0.''38 \times 0.''38$, covering a $12' \times 12'$ field for the larger, and a $6' \times 6'$ field for the smaller, CCD. Since the CCDs’ sensitivities peak in the R-band, a standard R filter was used for all of the observations, which were conducted on a total of 61 nights (29 for RQQs, 32 for LDQs), with a typical duration of ~ 6 hours per night. On each night only one AGN was monitored, as continuously as possible, and the typical sampling rate was about 5 frames per hour. The choice of exposure time depended on the brightness of the QSO and of the moon as well as the sky transparency. All these QSOs were chosen so that at least 2 – 3 comparison stars within about a magnitude of the QSO were simultaneously registered on the CCD frame. This redundancy allowed us

[†] URL <http://ned.ipac.caltech.edu/>

Table 1. The seven sets of radio-quiet (RQQ) and lobe-dominated quasars (LDQs) monitored in the present programme

Set No.	Object	Other Name	Type	RA(2000)	Dec(2000)	B (mag)	M_B (mag)	z	%Pol ^a (optical)	R^b
1.	0945+438	US 995	RQQ	09 48 59.4	+43 35 18	16.45	-24.3	0.226	—	<0.85
	2349-014	PKS 2349-01	LDQ	23 51 56.1	-01 09 13	15.45	-24.7	0.174	0.91	295
2.	0514-005	1E 0514-0030	RQQ	05 16 33.5	-00 27 14	16.26	-25.1	0.291	—	< 1.1
	1004+130	PG 1004+130	LDQ	10 07 26.2	+12 48 56	15.28	-25.6	0.240	0.79	195
3.	1252+020	Q 1252+0200	RQQ	12 55 19.7	+01 44 13	15.48	-26.2	0.345	—	0.52
	0134+329	3C 48.0	LDQ	01 37 41.3	+33 09 35	16.62	-25.2	0.367	1.41	8511
4.	1101+319	TON 52	RQQ	11 04 07.0	+31 41 11	16.00	-26.2	0.440	—	< -0.39
	1103-006	PKS 1103-006	LDQ	11 06 31.8	-00 52 53	16.39	-25.7	0.426	0.37	631
5.	1029+329	CSO 50	RQQ	10 32 06.0	+32 40 21	16.00	-26.7	0.560	—	< -0.23
	0709+370	B2 0709+37	LDQ	07 13 09.4	+36 56 07	15.66	-26.8	0.487	—	120
6.	0748+294	QJ 0751+2919	RQQ	07 51 12.3	+29 19 38	15.00	-29.0	0.910	—	0.21
	0350-073	3C 94	LDQ	03 52 30.6	-07 11 02	16.93	-27.2	0.962	1.42	1175
7.	1017+279	TON 34	RQQ	10 19 56.6	+27 44 02	16.06	-29.8	1.918	—	< -0.32
	0012+305	B2 0012+30	LDQ	00 15 35.9	+30 52 30	16.30	-29.1	1.619	—	57.5

^a Reference to the polarization data: Wills et al. (1992)

^b R is the ratio of the radio-to-optical flux densities (Sect. 3.1)

to identify and discount any comparison star which itself varied during a given night, and thereby ensured reliable differential photometry of the QSO.

Table 2 gives a log of our observations of the QSOs which we found to be intranight variables (or, probable variables). Table 3 gives the positions and apparent magnitudes of the comparison stars used for these and other QSOs whose DLCs are reported in this paper. Finding charts for all the comparison stars used in our programme can be found in Stalin (2002) and Stalin et al. (2003).

3.2 Data Processing

Preliminary processing of the images, as well as the photometry, was done using IRAF[‡]. Bias frames were obtained every night and the average bias frame was subtracted from all image frames after clipping the cosmic-ray (CR) hits. Dark frame subtraction was not carried out because the CCDs were cooled to -120°C and so the accumulation of thermal charge was negligible. The flat-fielding of the frames was done by taking several twilight sky frames which were median combined to generate the flat-field template which was then used to derive the final frames. The final step involved removing CR hits seen in the flat-fielded target frames using the facilities available in the MIDAS[§] software.

On a given night, the aperture photometry of the QSO and their chosen comparison stars present in each frame employed the same circular aperture to determine instrumental magnitudes, using the *daofind* and *phot* tasks in IRAF. The derived instrumental magnitudes were used to construct differential light curves (DLCs) of a given QSO relative to the chosen comparison stars as well as between all pairs of the comparison stars. On each night a range of aperture radii were considered and the one that minimized the variance

of the DLC of the steadiest pair of comparison stars was adopted; the mean value of the aperture radius used was $4.''0 \pm 1.''3$. We stress that the DLCs are not sensitive to the exact choice of aperture radius.

The B and R magnitudes and colours for each QSO and its comparison star were obtained from the USNO catalog[¶]; the difference between the $B - R$ colour indices of the QSO and at least one of its comparison stars was always found to be less than one magnitude, except for the LDQ 1103-006, where it was 1.2 mag (Table 3).

4 RESULTS

4.1 Intra-night and inter-night variability

In Figures 1 and 2 the derived DLCs are presented for the 3 LDQs and 3 RQQs that showed evidence of INOV on 12 nights. Out of these, 10 DLCs show clear INOV, while the remaining two DLCs are classified as ‘Probable Variable (PV)’ (Table 2). All these 12 DLCs display 3-point running averages of the respective original data sequences, taken for improving the signal/noise ratio. However, no averaging of the data points was done for the DLCs meant to show the observed single-point spikes which are displayed in Fig. 3. The entire set of DLCs obtained in our programme (113 nights) is presented in Stalin (2002) and Stalin et al. (2003). We note that the error bars shown on the data points are those given by the *phot* algorithm in IRAF; however, these nominal error bars are, for DAOPHOT reductions, too small by a factor of ~ 1.5 (Stalin 2002; GSSW03). So we have used this correction factor in the further analysis.

Table 2 provides information on the variability status for each night of monitoring, as inferred from the DLCs. For the variable and probable variable QSOs, we have also given the values of the parameter, C_{eff} which employs an statistical criterion similar to that of Jang & Miller (1997) with the added advantage that for each QSO we have DLCs relative

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

[§] Munich Image and Data Analysis System, designed and developed by the ESO

[¶] <http://archive.eso.org/skycat/servers/usnoa>

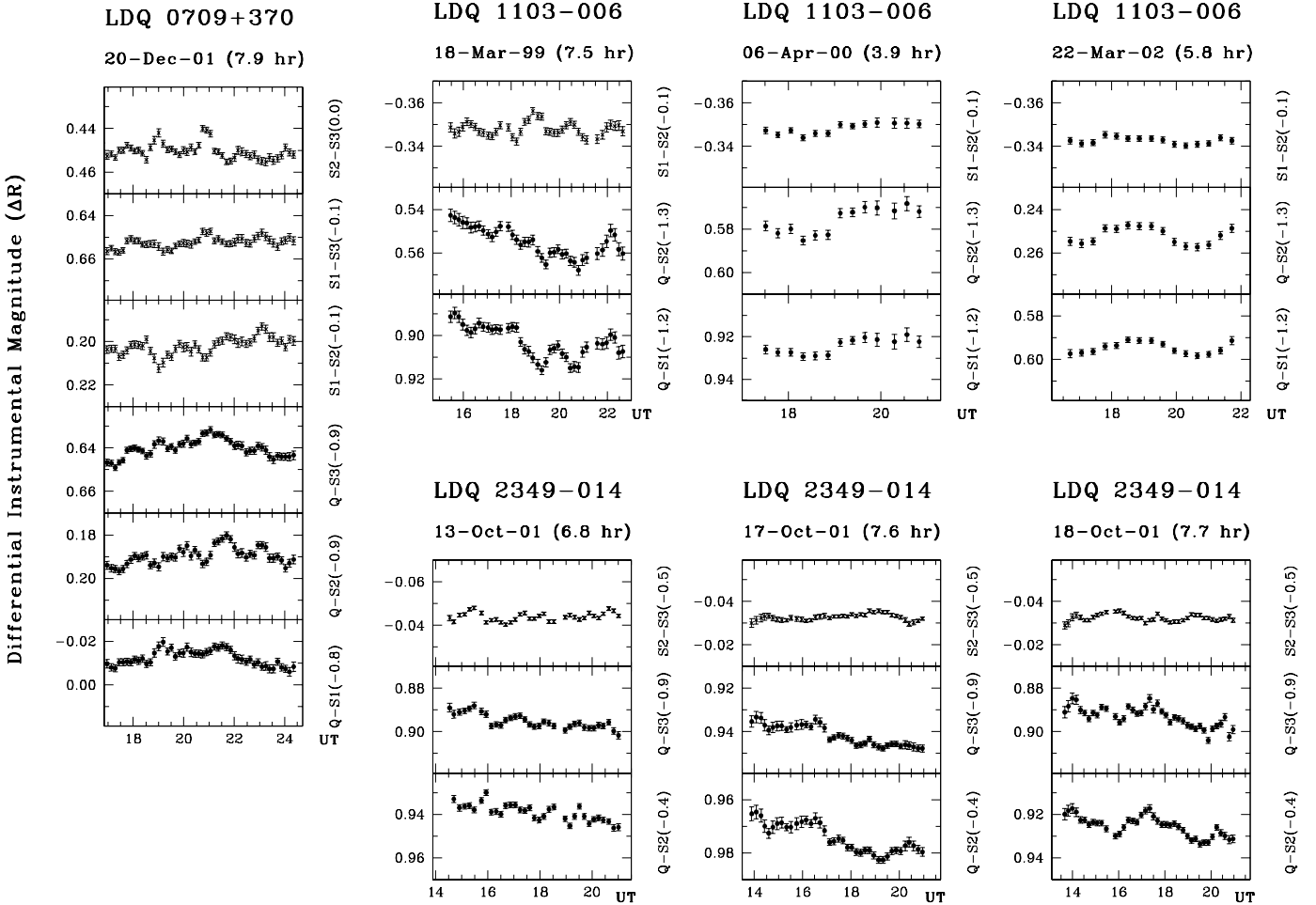


Figure 1. Differential light curves (DLCs) for the radio lobe-dominated quasars (LDQs) with a positive or probable detection of INOV. The name of the quasar, the date and the duration of observations are given at the top of each night’s observations. The upper panel(s) give the differential light curves (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. The numbers inside the parentheses are the differential color indices, $\Delta(B - R)$ for the respective DLCs.

to multiple comparison stars (see GSSW03). This allowed us to discard any INOV candidates for which the multiple DLCs do not show clearly correlated trends, both in amplitude and time. For a given DLC, we take the ratio of its standard deviation and the mean σ_i of its individual data points. This ratio, C_i , for the i^{th} DLC of a given QSO has the corresponding probability p_i that the DLC is non-variable, assuming a normal distribution. We then compute the joint probability, P , by multiplying the values of p_i ’s for individual DLCs available for the QSO. This effective C parameter, C_{eff} , corresponding to P , is given in Table 2 for each variable or probable variable DLC. Our criterion for variability is $C_{\text{eff}} > 2.57$, which corresponds to a confidence level in excess of 99%. The criterion for ‘probable variable’ is $C_{\text{eff}} > 2.00$ which corresponds to a confidence level $> 95\%$. The last column of Table 2 gives for each DLC the value of of peak-to-peak variability amplitude, $\psi \equiv [(D_{\text{max}} - D_{\text{min}})^2 - 2\sigma^2]^{1/2}$. Here, D is the differential magnitude, $\sigma^2 = \eta^2 < \sigma_{\text{err}}^2 >$,

with η the factor by which the average of the measurement errors (σ_{err} , as given by *phot* algorithm) should be multiplied; we find $\eta = 1.50$ (Stalin 2002; GSSW03).

As an added precaution, we have used the colour information on the comparison stars (Table 3) to check if the inferred INOV of any of the QSOs is spurious, arising from a combination of a large differential colour index $\Delta(B - R)$, for the QSO DLCs and the varying airmass with zenith distance during the night. For each night when the QSO DLCs showed (correlated) INOV and all of those DLCs had large $\Delta(B - R)$ (amplitude significantly higher than 1-mag), the apparent INOV of the QSO could conceivably be spurious, unless at least one of the star-star DLC on the same night also had similarly large $\Delta(B - R)$ and yet showed no systematic trend over the night. In the present sample, a possible such case of a QSO designated as variable is the RQQ 1029+329 (05 April 2000). By generating a star-star DLC with a large differential colour index $\Delta(B - R) = -1.9$ from

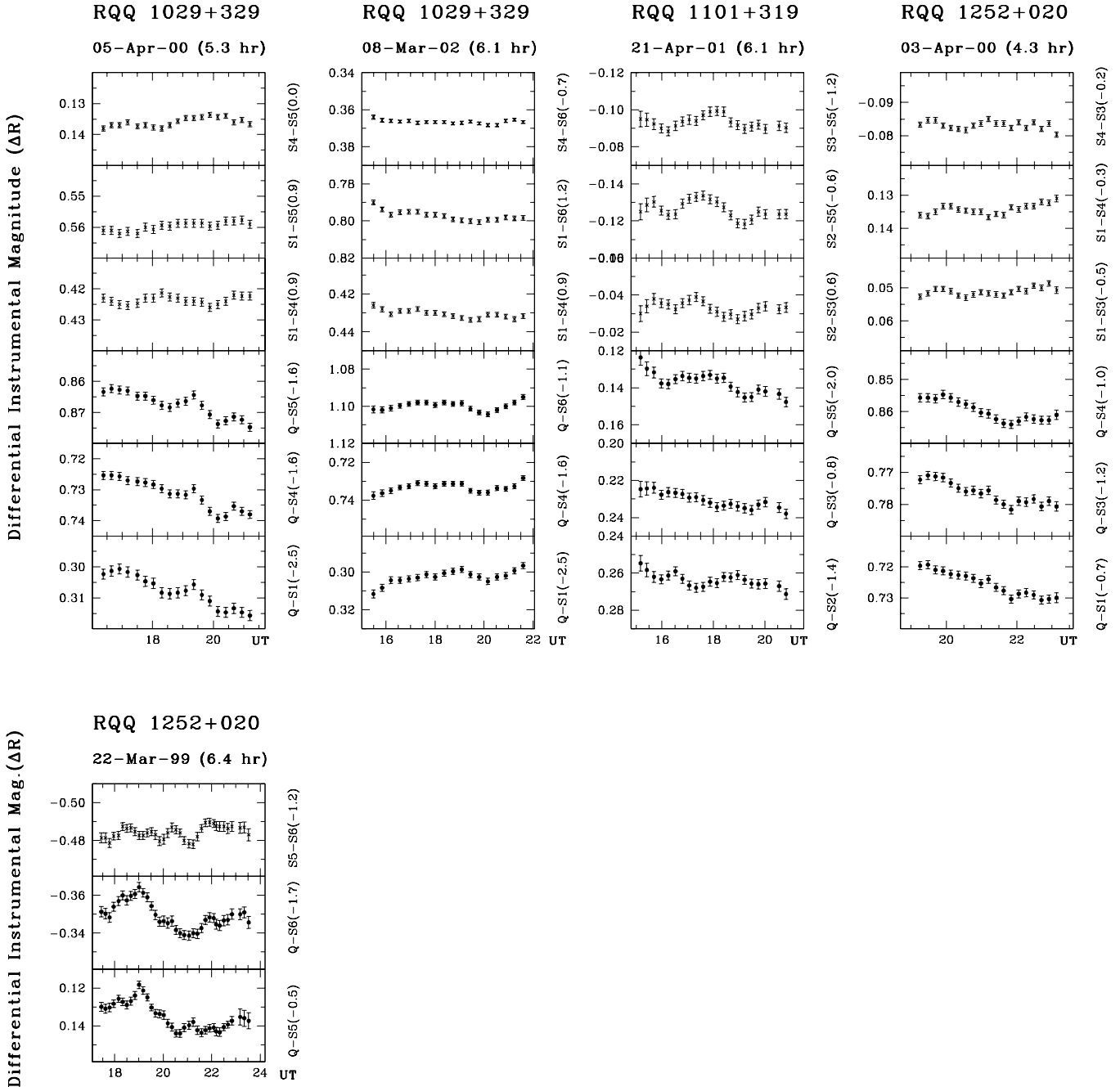


Figure 2. Differential light curves (DLCs) for the radio-quiet quasars (RQQs) for which INOV was detected. The format is identical to that of Fig. 1.

the frames taken on the same night of 05 Apr 2000, it has already been shown in GSSW03 that even such a large value of $\Delta(B - R)$ did not produce a systematic variation in the DLC. Therefore, the inferred INOV of the RQQ cannot be an artefact of the similarly large colour differences that exist between this RQQ and its comparison stars.

Another potential source of spurious variability in such aperture photometry is the contamination arising from the host galaxy of the target AGN. As pointed out by Carini et al. (1991) intra-night fluctuations in the atmospheric seeing could result in appreciably variable light contributions from the host galaxy within the aperture. Recently, Cellone,

Romero & Combi (2000) argued that such spurious variations can be substantial for AGN with bright galaxy hosts, particularly when small photometric apertures are used. Our DLCs are very unlikely to be affected by this, since not only have we used sufficiently large apertures for photometry (Table 2), but also all the QSOs in our sample are an order-of-magnitude more luminous than their putative host galaxies, with the sole exception of the nearby LDQ 2349–014. In this case, host galaxy is seen on our CCD images; hence, we used a rather large aperture ($6''$ radius). Moreover, we find that either the seeing disk (as estimated from a star on the CCD frames, which was thus monitored concurrently with

Table 2. Log of the optical observations of RQQs and LDQs

Object	Type	Date	N	T (hr)	INOV status	C_{eff}	ψ (%)
0945+438	RQQ	15.01.99	44	8.0	NV		
		26.02.00	31	6.3	NV		
		23.01.01	24	6.6	NV		
2349-014	LDQ	13.10.01	34	6.8	V	3.6	2.2
		17.10.01	39	7.6	V	3.1	1.5
		18.10.01	40	7.7	V	3.2	1.6
0514-005	RQQ	09.12.01	25	5.3	NV		
		10.12.01	23	5.8	NV		
		19.12.01	35	7.5	NV		
1004+130	LDQ	27.02.99	30	4.3	NV		
		16.02.99	36	6.5	NV		
		29.03.00	21	3.8	NV		
		30.03.00	26	4.6	NV		
		18.02.01	42	5.5	NV		
		24.03.01	50	6.4	NV		
1252+020	RQQ	22.03.99	36	6.4	V	3.3	2.3
		09.03.00	29	6.1	NV		
		03.04.00	19	4.3	V	3.6	0.9
		26.04.01	20	4.6	NV		
		18.03.02	19	7.3	NV		
0134+329	LDQ	07.11.01	33	6.5	NV		
		08.11.01	32	6.7	NV		
		13.11.01	46	8.6	NV		
1101+319	RQQ	12.03.99	39	8.5	NV		
		04.04.00	22	5.6	NV		
		21.04.01	21	6.1	V	2.6	1.2
		22.04.01	21	5.8	NV		
1103-006	LDQ	17.03.99	23	3.8	NV		
		18.03.99	40	7.5	V	3.1	2.4
		06.04.00	13	3.9	PV	2.1	1.2
		25.03.01	28	7.2	NV		
		14.04.01	19	4.5	NV		
		22.03.02	15	5.8	PV	2.2	0.7
1029+329	RQQ	02.03.00	19	5.0	NV		
		05.04.00	19	5.3	V	4.3	1.3
		23.03.01	20	5.8	NV		
		06.03.02	31	8.5	NV		
		08.03.02	17	6.1	V	2.8	1.1
		20.01.01	29	6.5	NV		
0709+370	LDQ	21.01.01	29	6.2	NV		
		25.01.01	31	7.1	NV		
		20.12.01	49	7.9	V	3.1	1.4
		21.12.01	48	7.5	NV		
		14.12.98	22	7.6	NV		
		13.01.99	56	8.3	NV		
0748+294	RQQ	09.12.99	26	5.1	NV		
		24.11.00	28	5.4	NV		
		01.12.00	32	6.0	NV		
		25.12.01	30	5.4	NV		
		14.11.01	31	6.6	NV		
		15.11.01	26	5.5	NV		
1017+279	RQQ	18.11.01	25	5.7	NV		
		14.03.99	43	7.3	NV		
		14.01.00	33	7.1	NV		
0012+305	LDQ	27.02.00	33	8.1	NV		
		18.01.01	17	3.6	NV		
		20.01.01	14	3.2	NV		
		24.01.01	14	2.9	NV		
		14.10.01	20	5.7	NV		
		21.10.01	22	5.7	NV		
		22.10.01	24	6.2	NV		

the QSO), remained steady, or sharpened slightly during the night, implying that the observed gradual fading of the QSO (Figs. 1 and 2) cannot be understood in terms of any seeing variations during the nights the QSO was monitored.

Below we give brief remarks on individual QSOs for which we have positive or probable detection of INOV, in increasing order of redshift.

LDQ 2349-014, $z = 0.174$: On each of the three nights the comparison stars S2 and S3 remained steady, and the QSO DLCs relative to both stars show a correlated decline by about 2% over the roughly seven hours of monitoring (Fig. 1). Moreover, between 21.3 UT on 17 October 2001 and 13.5 UT on the next night the QSO brightened by $\sim 5\%$ (note the different ordinate labels).

LDQ 1004+130, $z = 0.240$: This QSO was monitored on six nights. In Fig. 3 we present the DLCs for 24 March 2001, which shows a large spike of over 3% ($\sim 9\sigma$) at 16.23 UT relative to both available comparison stars, which themselves remained steady. The QSO brightened by $\sim 2\%$ between 20 UT on 29 March 2000 and the next night's observations which began at 16.0 UT (Stalin 2002; Stalin et al. 2003).

RQQ 1252+020, $z = 0.345$: Over the five nights of monitoring correlated variability of $\sim 2\%$ amplitude occurred on 22 March 1999 (Fig. 2). On 3 April 2000, the DLCs of the QSO against all three stars showed a gradual fading by $\sim 1\%$ during the 4.1 hours of monitoring (Fig. 2). As discussed in GSSW03, this variation is well above the noise, and is opposite to that expected from the steady improvement observed in the atmospheric seeing over the night.

RQQ 1101+319, $z = 0.440$: Of the four nights this QSO was monitored, INOV was detected on 21 April 2001. Against all three comparison stars, the QSO flux declined by about 1.5% over the course of the night (Fig. 2). Although noisier than usual, the star-star DLCs do not show any such systematic trend.

LDQ 1103-006, $z = 0.426$: This QSO was observed on six nights. Unfortunately, only two reasonably steady comparison stars could be found. The DLCs of 18 March 1999 show probable INOV, where the LDQ dimmed by about 2% during the first three hours of observations and thereafter remained fairly steady (Fig. 1). On 6 April 2000 there was a probable variation involving an increase in QSO brightness of $\sim 1\%$ during the ~ 4 hours of monitoring (Fig. 1). On 22 March 2002, this QSO showed a probable variation (Fig. 1). On 25 March 2001, an apparent variability in the form of a spike of about 2% ($\sim 4\sigma$) was seen at 21.13 UT (Fig. 3).

RQQ 1029+329 (CSO 50), $z = 0.560$: This QSO was observed on five nights, and DLCs for two of them are shown in Fig. 2. On 5 April 2000, the QSO slowly dimmed by about 2% against all three stars during the course of the night; the seeing steadily improved during the night and, if of importance, would have yielded a small gradient opposite to that observed (GSSW03). On 8 March 2002, against all three comparison stars (in particular, S4 and S6 which were very steady), the RQQ showed a significant variability (Fig. 2), while the atmospheric seeing remained very steady throughout the session. During the remaining two nights (23 March 2001 and 6 March 2002) spikes of $\sim 1.7\%$ ($\sim 3-4\sigma$) were detected (Fig. 3; Stalin et al. 2003).

LDQ 0709+370, $z = 0.487$: On one of the five nights this QSO was monitored, 20 December 2001, the QSO brightened by about 1% against all three comparison stars during the

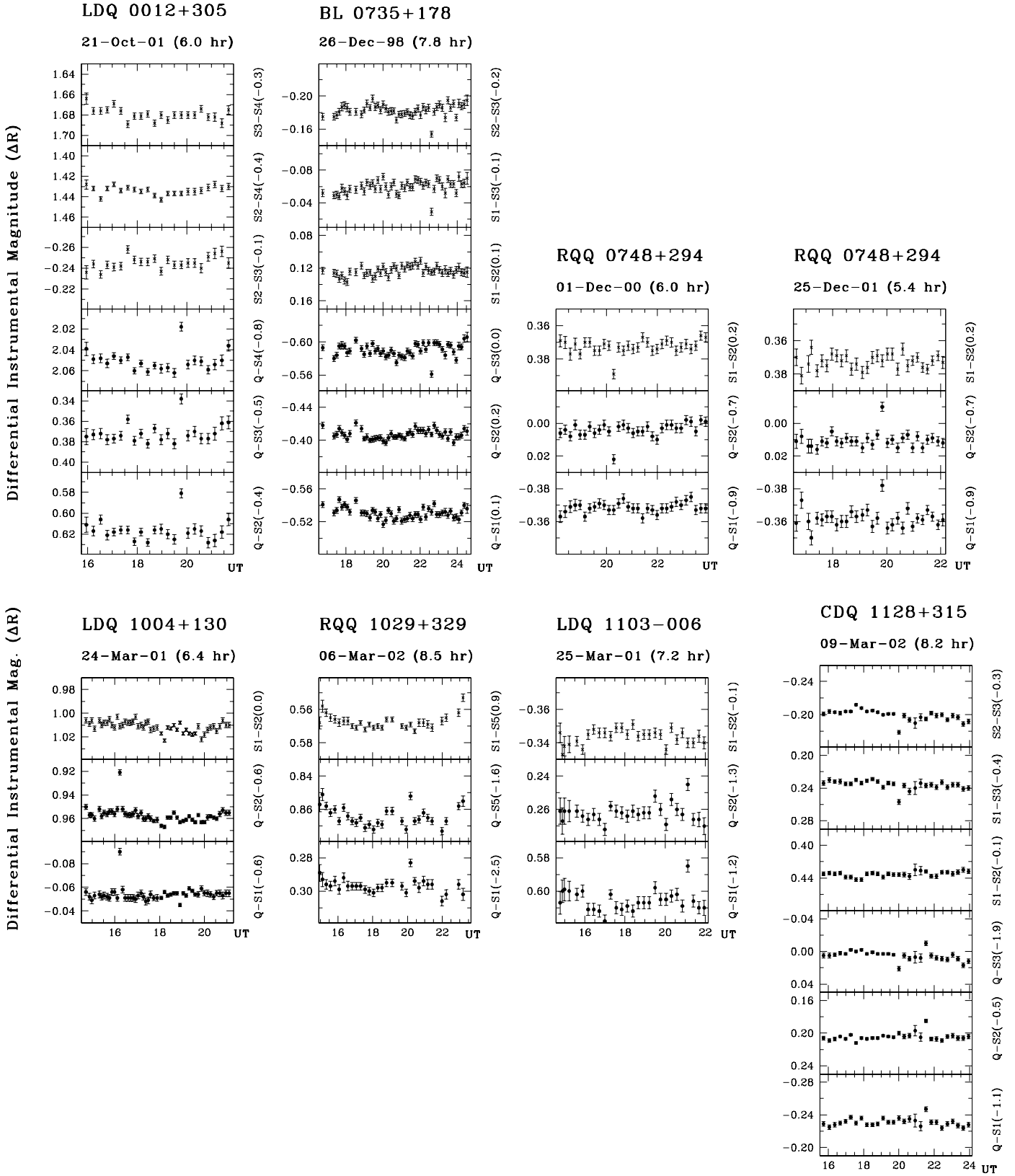


Figure 3. DLCs for the dates on which single-point ‘spikes’ were seen either on the QSO DLC or on the star-star DLC, displayed as in Fig. 1.

first half of the night and then returned to its initial level during the second half of the night (Fig. 1).

RQQ 0748+294, $z = 0.910$: This object was also observed by us earlier, and probable (spike) INOV was noted (Paper IV). During the present campaign, it was monitored for six nights, of which the last four had excellent sensitivity and coverage. On 25 December 2001 the QSO DLCs showed a $\sim 2\%$ spike at 19.83 UT ($\sim 4\sigma$) (Fig. 3). Also, a significant star spike was observed at 20.28 UT on 1 December 2000 (star 2 rose by $\sim 1.8\%$; 4σ) (Fig. 3).

LDQ 0012+305, $z = 1.619$: All measurements over six nights were fairly noisy due to the faintness of the QSO ($m_B = 17.2$). A spike of 4% ($> 4\sigma$) was seen for this QSO at 19.78 UT on 21 October 2001 (Fig. 3).

4.2 Long term optical variability (LTOV)

Here we comment upon the subset of the four RQQs and the three LDQs for which significant changes were found in their R-band flux over the longer period we monitored them. In increasing order of redshift they are:

RQQ 0945+438, $z = 0.226$: Between 26 February 2000 and 23 January 2001 this QSO was found to have dimmed by about 0.07 mag.

LDQ 1004+130, $z = 0.240$: A drop of 0.09 mag is observed between 16 March 1999 and 29 March 2000. No level fluctuations exceeding 0.02 mag were noticed in four subsequent epochs of observations (Fig. 4).

RQQ 1252+020, $z = 0.345$: This QSO was observed on 5 nights over a three year period beginning 22 March 1999. It brightened by 0.18 mag between 3 April 2000 and 26 April 2001, and had faded by 0.10 mag at the time of the last observation on 18 March 2002.

LDQ 1103–006, $z = 0.426$: This QSO was monitored on 6 nights and was steady for the first three of them, from 17 March 1999 to 6 April 2000 (Fig. 5). By the time of the next observation on 25 March 2001, it had brightened by 0.32 mag, and both subsequent measurements (until 22 March 2002) found it at the same level (to within 0.25%).

RQQ 1101+319, $z = 0.440$: A drop of 0.2 mag over the course of roughly one year (12 March 1999 to 4 April 2000) was seen, with a rise of about 0.07 mag observed by the time of the next observation on 21 April 2001.

RQQ 0748+294, $z = 0.910$: We monitored this RQQ on 6 nights between 14 December 1998 and 25 December 2001 (Fig. 6). The comparison stars were always stable to within 1%. A dip of 0.23 mag was found between 14 December 1998 and 13 January 1999; by the time of the next observations on 9 December 1999 the source had recovered to its original brightness level, and was found at the same level (to within 0.25%) in our subsequent measurements during the following two years (Sect. 5.3).

LDQ 0012+305, $z = 1.619$: This LDQ was monitored on three nights in January 2001 and on another three nights in October 2001. It remained stable within each month, but dropped by 7% during the intervening period (between January 2001 and October 2001).

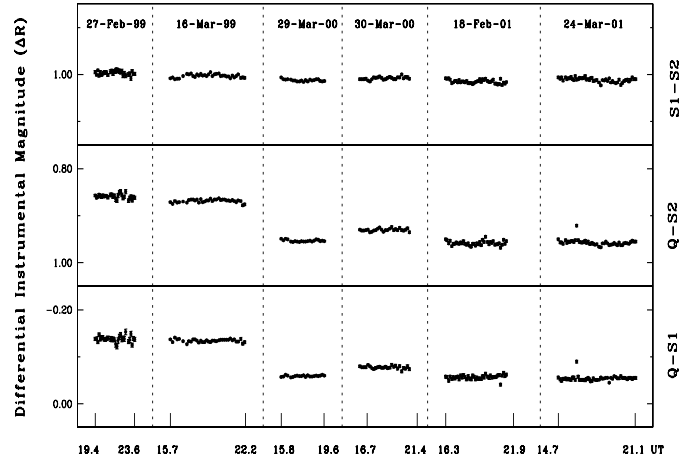


Figure 4. Long-term variations in the DLCs of the LDQ 1004+130, with all star-star and QSO-star DLCs plotted as labelled.

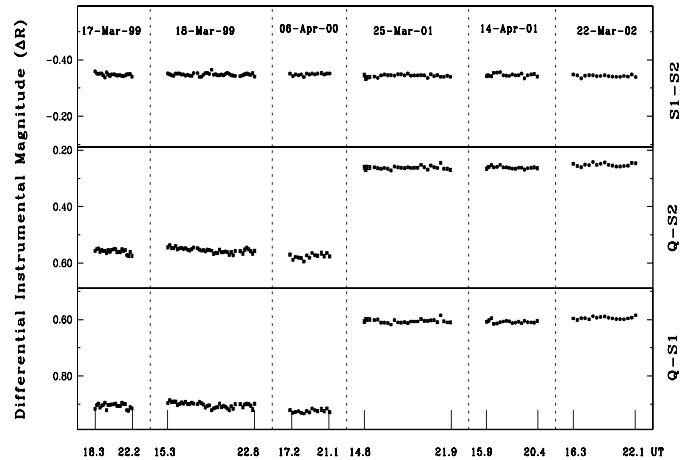


Figure 5. Long-term variations in the DLCs of the LDQ 1103–006, displayed as in Fig. 4.

5 DISCUSSION

5.1 Intra-night Optical Variability (INOV)

In Sect. 2 we mentioned the marked diversity in the estimates of duty cycles for INOV in various classes of AGN. Romero et al. (1999) estimated duty cycles for RQQs of only about 3%, while for X-ray selected blazars this duty cycle was 28% and for radio selected quasars (including blazars) 72%, which is comparable to the estimates (over 80%) by Carini (1990) and Heidt & Wagner (1996) for (radio loud) blazars. However, de Diego et al. (1998) concluded that the probabilities of detecting INOV for RQQs and CDQs were statistically indistinguishable; their implied value for our typical 6 hour duration of monitoring would be $\sim 25\%$.

Both classes of objects in our matched sample were monitored with equally high sensitivities for comparable periods: the mean observing time for RQQs was 6.4 ± 1.2 hours per night over 29 nights, while for LDQs it was 5.9 ± 1.5

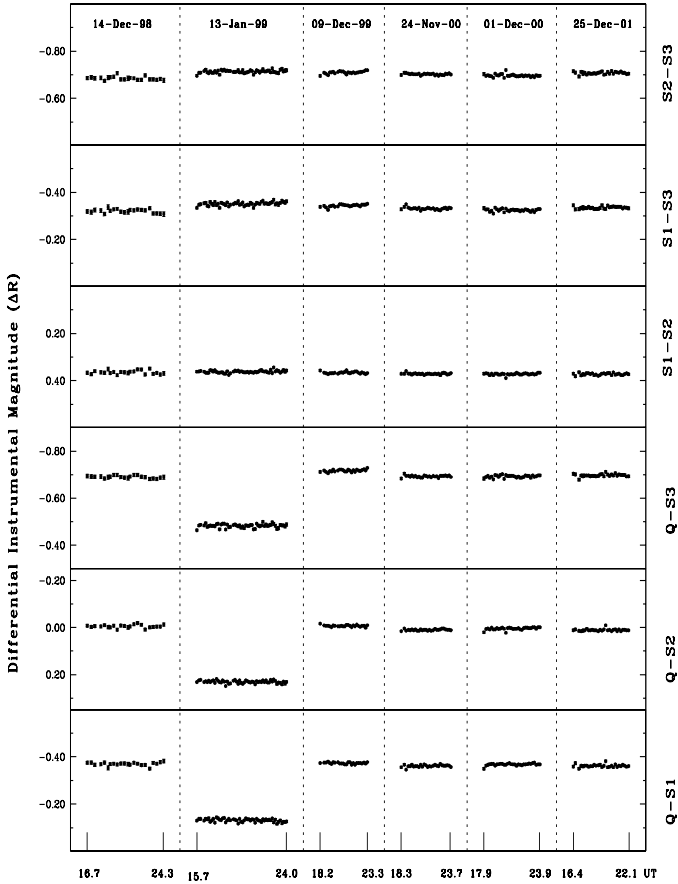


Figure 6. Long-term variations in the DLCs of the RQQ 0748+294, displayed as in Fig. 4.

hours per night over 32 nights. Thus it is possible to directly compare the INOV duty cycles for these two AGN classes. Following Romero et al. (1999) we define the duty cycle, DC, so that the contribution to the duty cycle has been weighted by the number of hours (in its rest frame) for which each source was monitored,

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

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 source out of a total of n sessions for the selected AGN class, and N_i equals 0 or 1, depending on whether the object was non-variable or variable, respectively, during Δt_i .

For RQQs, counting only observing sessions for which the INOV was clearly detected, we find the DC = 17%. Our value falls roughly mid-way between the lower estimates published by Jang & Miller (1997) and by Romero et al. (1999), and the higher estimate of de Diego et al. (1998), though we note that the latter analysis technique is less trustworthy (Sect. 2).

Turning to LDQs, we find a DC of 9% for a clear detection of INOV. An additional possible contribution of 6% comes from the two cases of probable detection. So the DC

including all likely INOV for the LDQs is about 15%. Given the rather small number of detections that resulted despite the substantial length of our observations, one clearly cannot claim any statistically significant difference between the DCs of INOV for the RQQ and LDQ classes. Interestingly, the ranges of INOV amplitudes for both RQQs and LDQs are also found to be very similar ($\psi < 3\%$) (Table 2; Sect. 4.1) and this is a key result of the present study. It is also noteworthy that a close similarity between LDQs and RQQs in terms of INOV duty cycle extends even to BL Lac objects if only their small-amplitude INOV ($\psi < 3\%$) is considered (see, Fig. 2 of GSSW03). A possible explanation of these similarities in the INOV characteristics is outlined below.

A key motivation of our program was to assess the role of relativistic beaming in the INOV of AGN classes other than blazars for which the bulk of all variability is believed to arise from instabilities in their relativistic jets. In our monitoring program, both the INOV duty cycle and amplitudes for BL Lacs are found to be much higher than for the RQQs (GSSW03) and also compared to LDQs (present work). Therefore it is relevant to ask to what extent the modest variations of the RQQs and LDQs might be understood within the conventional relativistic jet paradigm if one postulated that such jets exist (on optically emitting scale lengths) even in RQQs, and also accepts the conventional wisdom that, in general, the axes of QSOs are mildly misaligned from us (e.g., Barthel 1989; Antonucci 1993). In GSSW03, we argued in favour of such a possibility and, likewise, we now explore this point further, taking a clue from the BL Lac object OJ287 monitored by us.

For objects whose flux densities are relativistically beamed, the observed degree of flux variability and consequently, the duty cycles, can be strongly influenced by the beaming, since any intrinsic flux variations associated with the relativistic outflow will have their time-scales shortened and amplitudes boosted in the observer's frame. As usual, the Doppler factor is defined as $\delta = [\Gamma(1 - \beta \cos \theta)]^{-1}$, where $\beta = v/c$, $\Gamma = (1 - \beta^2)^{-1/2}$ is the bulk Lorentz factor of the jet, and θ is the viewing angle. Then the observed flux density, S_{obs} is given in terms of the intrinsic flux density, S_{int} (e.g. Urry & Padovani 1995)

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

Here, $p = 3 - \alpha$ for a moving disturbance or blob in the jet; the spectral index of the emission, $\alpha \equiv d \ln(S_\nu) / d \ln(\nu)$ and we have assumed $\alpha = -1$ when evaluating this expression (Stocke et al. 1992). Similarly, due to the beaming, the observed time scale becomes shortened as $\Delta t_{obs} = \Delta t_{int}(1+z)/\delta$.

In Fig. 7 we illustrate the effect of the Doppler beaming on the observed DLCs assuming the spherical blob model; conclusions for the continuous jet model are similar (GSSW03). We start with a DLC of the BL Lac object 0851+202 (OJ 287) which exhibited a large ($\sim 5\%$) and rapid (~ 0.8 hour) variation on 28 March 2000 (Stalin 2002; Sagar et al. 2003). For this source, $\delta_o = 14.88$ has been estimated by Zhang, Fan & Cheng (2002). We now use this DLC to simulate light curves for lower values of δ , as would be seen by a observers at a larger viewing angles to the jet, by mapping the observed DLC onto the 'amplitude-time' plane corresponding to chosen values of δ . This mapping

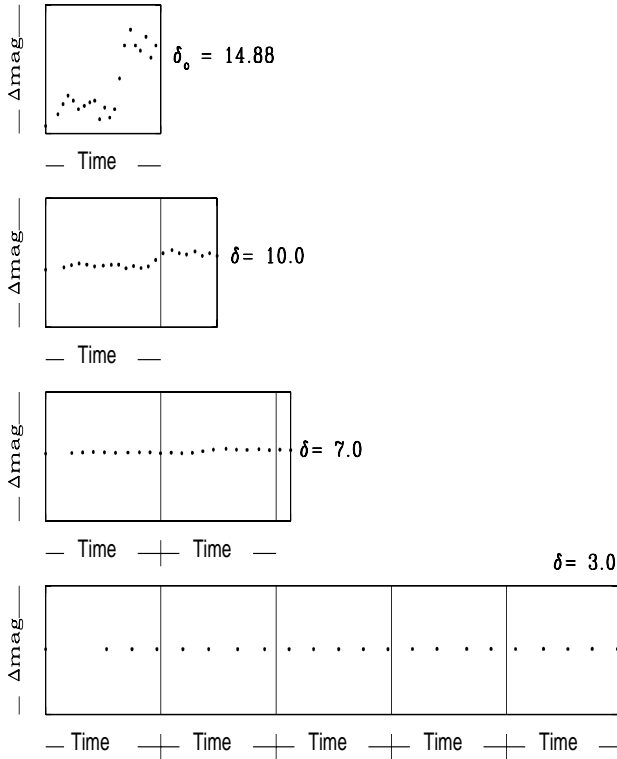


Figure 7. The top panel presents the R-band light curve of the BL Lac object 0851+202 (OJ 287), showing a $\sim 5\%$ fluctuation, observed on 28 March 2000. Subsequent panels show its translation to progressively smaller Doppler factors, corresponding to larger viewing angles, assuming the model of a discrete moving blob in the relativistic jet. Each rectangular window shows an equal time interval (4.2 hours in this case) in the observer’s frame, and the total amplitude range, Δ mag, for each panel is 0.1-mag., relative to the same comparison star.

is achieved simply by compressing the observed DLC amplitudes by a factor $(\delta/\delta_o)^p$ and, simultaneously, stretching the DLCs along the time axis by a factor (δ_o/δ) , where δ_o and δ are the original (actual) and lower adopted values of the Doppler factor, respectively.

From these (partially) Doppler de-beamed DLCs (Fig. 7), it is evident that even an observer at only a marginally misaligned direction to the jet will monitor a drastic reduction in both the amplitude and rapidity of the INOV for the same BL Lac object which appears highly variable to a better aligned observer. For example, if $\theta = 3.^\circ75$ for the jet of OJ 287, the estimated $\delta_o = 14.88$ corresponds to $\beta = 0.9966$. This would give $\delta = 10$ for a modestly misaligned jet with $\theta \simeq 6^\circ$, $\delta = 7$ for $\theta \simeq 7.^\circ5$ and $\delta = 3$ for $\theta \simeq 13^\circ$; such misalignments (or even somewhat larger ones corresponding to even smaller δ) are believed to be typical of LDQs (Barthel 1989) and RQQs as well (Antonucci 1993). The simulated light curves for viewing angles greater than $\sim 10^\circ$ show barely detectable INOV, as is indeed observed for both LDQs and RQQs (Figs. 1 & 2). From this we surmise that the mere absence of pronounced INOV in RQQs in no way rules out the possibility that they have optical synchrotron jets as active intrinsically (albeit some-

what more misdirected) as those in BL Lacs (GSSW03). An independent support to this assertion comes from the similarity found here in the INOV of RQQs and LDQs, since the central engines of LDQs are in any case believed to emit relativistic synchrotron jets (e.g., Urry & Padovani 1995).

5.2 Spikes

Strong single-point fluctuations, or spikes, were noted for several RQQs in Paper IV, and similar events were noted in our present monitoring campaign of AGN (Fig. 3). We did not see such excursions in any of the star–star DLCs from the programme reported in Paper IV. This led us to conclude that these events were probably intrinsic to the RQQs, though we noted that simultaneous detection at different sites was essential to confirm the reality of such events. However, our present measurements have greater sensitivity, thanks to the new Wright CCD, so we were able to make a careful search for this type of fluctuations in the entire data set, including the DLCs of CDQs and BL Lacs that are reported in detail elsewhere (Stalin et al. 2003; Stalin 2002). In performing this search we conservatively define a spike as a single point fluctuation visible simultaneously in multiple DLCs involving the same object, after which the flux returns to essentially the pre-spike level and the amplitude of the fluctuation is a minimum of 2.5σ (corrected by the factor of 1.5, Sect. 4.1) on at least two of the DLCs involving the object showing the spike.

Based on these criteria we have identified 15 spikes associated with the AGNs in our sample (including all the four types) and 20 spikes associated with their comparison stars. Since we typically derive DLCs for 2 or 3 comparison stars for each QSO, if these spikes were non-intrinsic random events, one would naively expect a couple of times as many spikes to be seen for the stars than for the QSOs. But, since on average, the quasars are somewhat fainter than the comparison stars, the relative number of detectable spikes would be slightly enhanced for the QSOs. We note that all but one of the spikes was positive; the exception was for the Star 3 in the field of the LDQ 0709+370 on 20 January 2001 at 18.19 UT where a negative deviation of $\sim 1.7\%$ ($> 5\sigma$) was found.

A single stellar spike in Star 2 for RQQ 0748+294, plotted in Fig. 3, was mentioned above. In Fig. 3 we also plot an additional two stellar spikes discovered in this wider data base, one from Star 3 in the comparison group for the BL Lac 0735+178 on 26 December 1998 at 22.62 UT, and one from Star 3 in the comparison group of the CDQ 1128+315 on 9 March 2002 at 20.00 UT; note that this blazar also shows a spike at 21.53 UT on the same night. A table containing the details of these spike data will appear in Stalin et al. (2003).

We have determined the flux density of each spike, using the R magnitudes of the corresponding star or AGN, as follows. We convert the R magnitudes of the stars, taken from the USNO catalog, into flux densities and multiply by the average magnitude fluctuation of the spike. For the spikes on the AGN, since the R magnitudes of the AGN can differ significantly from those tabulated in the USNO catalog (due to long-term variability), we determined these instead by adding our observed mean differential magnitudes (QSO–star) on the night of the spike to the USNO

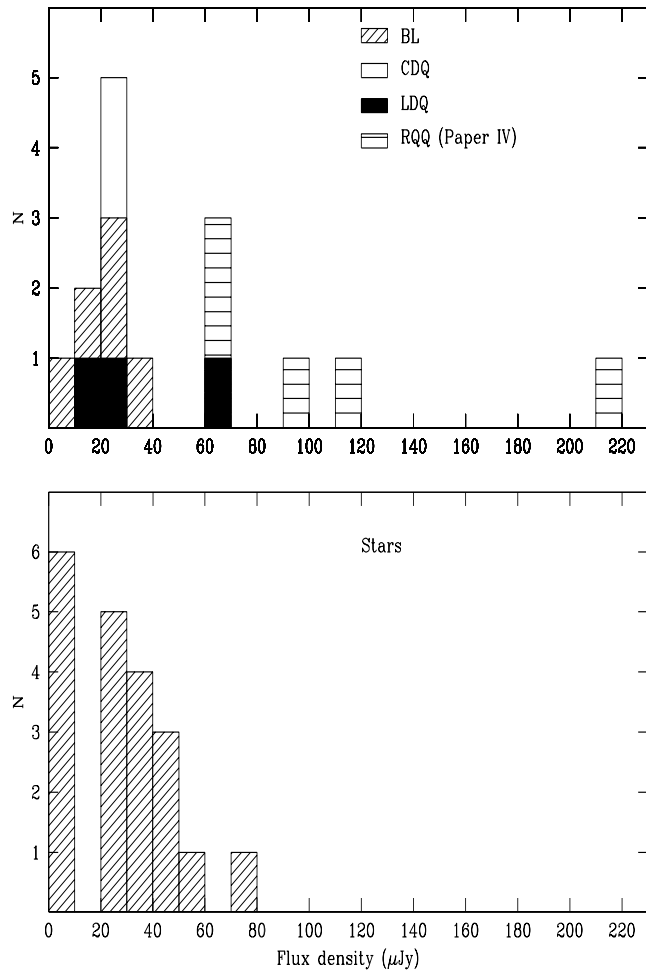


Figure 8. Histogram of flux densities of the “spikes” detected in both the current programme and those reported in Paper IV. The lower panel gives the distribution of fluxes for the spikes seen in the DLCs between the comparison stars and the upper panel shows the same as seen in the DLCs between the different classes of AGN and the comparison stars.

R-magnitudes of the corresponding stars and then taking an average of these values.

Fig. 8 shows a histogram of the flux densities attributable to these various spikes. In that our more sensitive observations have detected many cases of spikes even in the DLCs of the comparison stars, our earlier tentative conclusion (Paper IV) that since these had been found to occur only in the RQQs, and were therefore likely to be intrinsic to the RQQs, is not confirmed. If, as indicated by Fig. 8, these spikes are practically as common in QSOs as in stars, the simplest interpretation would be that they are caused by compact cosmic ray hits. It is also possible that some of them are of unknown instrumental origin. Yet it is worth noting that six of the seven most powerful spikes (those above $60\mu\text{Jy}$) are associated with the QSOs and not with the stars, so that we may still be observing some intrinsic ultra-rapid QSO variability. Possible explanations for such extreme events include brief periods during which coherent emission processes can be important (e.g. Lesch &

Pohl 1992; Krishan & Wiita 1990, 1994; Kawaguchi et al. 1998) or perhaps extreme turbulence and fortuitous intense Doppler boosting of emission from a dense or highly magnetized portion of the jet flow temporarily moving very close to the line of sight (e.g. Gopal-Krishna & Wiita 1992).

5.3 Long-term optical variability (LTOV)

As expected (e.g. Smith et al. 1990) nearly all QSOs which we monitored for extensive periods (> 2 months) exhibited significant amounts of LTOV. The RQQs 0945+438, 1252+020, 0748+294 and 1101+309 as well as the LDQs 1004+130, 1103–006, and 0012+305 exhibited significant changes, as described in Sect. 4.2. In addition, the LDQ 0709+370 showed a variation of about 3% between January and December 2001.

The only object not observed to have varied over month/year timescales is the RQQ 1029+329 (CSO 50), which was observed on five nights over the span of two years; it did however, show weak but clear INOV on two of these nights (GSSW03; Fig. 2). The other five objects in our sample (RQQs: 0514–005, 1017+279; LDQs: 2349–014, 0134+329, 0350–073) were only observed for total time baselines between 4 days and 6 weeks, so the lack of LTOV detection for them is not surprising.

Although our long-term sampling was not frequent enough to allow estimates for possible physical timescales to be obtained, we must remark upon the peculiar behaviour of the RQQ 0748+294 ($z = 0.910$) which was rather evenly sampled between December 1998 and December 2001 (Fig. 6). For the first and the last four measurements this object showed a constant brightness to within one percent, but on the night of 13 January 1999 it was about 0.2 mag fainter. While a relatively brief brightening of this order is explicable in many scenarios, such a dip is somewhat unexpected. We suggest that this dimming may correspond to a partial eclipse of the optical continuum source with a duration of less than six months in the source frame. A sufficiently warped or otherwise thickened portion of the accretion disk at roughly 100 Schwarzschild radii from a $10^8 M_\odot$ putative central black hole could block a significant fraction of the optical continuum emission from the inner portion of the disk for some months.

While our sample is rather small, there is no obvious difference in the behaviour of RQQs and LDQs in terms of optical variability on month-to-year timescales. This is in accord with the conclusions reached by Paltani & Courvoisier (1994) from their study of IUE data for radio-loud and radio-quiet QSOs in the ultraviolet.

6 CONCLUSIONS

The observations reported here in detail have placed on a firm footing the phenomenon of optical intra-night variability of optically luminous quasars of non-blazar type (both radio-quiet and lobe-dominated; also see GSSW03). The dense temporal sampling over long duration, together with the good sensitivity attained in our campaign using CCDs as N-star photometers, has clearly demonstrated that small amplitude (typically 0.01–0.03 mag) variations on timescales of hours are real. Even though the percentage luminos-

ity variation implied by the INOV of these luminous RQQs and LDQs is small, the total power involved is still so enormous as to render a starburst/supernova explanation (e.g. cid Fernandes et al. 1996) untenable for these rapid events.

Although our full programme covered BL Lacs and CDQs as well (see, GSSW03; Sagar et al. 2003; Stalin et al. 2003), in this paper we have provided results for a subsample of 7 RQQs and 7 LDQs matched in both redshift and optical power. A key result of our observations is that there is no significant difference in either the amplitude or duty-cycle of INOV between these two classes of non-blazar AGN. We thus infer that *the radio loudness of a quasar alone is not a sufficient condition for a pronounced INOV.*

Secondly, our expanded study of single-point fluctuations which occurred on the time scale smaller than ~ 15 min (including those seen on the DLCs of CDQs and BL Lacs) leads to the conclusion that, with the possible exception of the strongest ones, most of the spikes are probably caused by cosmic-ray hits. To confirm the origin of such spikes, it would be desirable to try to simultaneously observe such events from two independent observatories.

We have also presented some limited, but interesting, results on longer-term (month to year) variability of these non-blazar AGNs. Again we find no significant difference between the RQQs and LDQs, for both of which long-term variability is similarly common. We speculate that the 0.2 mag dip in the light-curve of the RQQ 0748+294 on 13 January 1999 is due to partial occultation of the optical continuum source, perhaps by a non-axisymmetric disk deformation.

While our data cannot exclude accretion disk flares as the source of the much milder and rarer intranight optical variability observed for RQQs and LDQs, as compared to BL Lacs (Sect. 1), it does not preclude a substantial contribution to this type of flux variability coming from blazar-like relativistically beamed emission. In Sect. 5.1 and GSSW03 we have demonstrated that a typical RQQ light-curve can be derived from an observed blazar light-curve even if the RQQ possesses a jet intrinsically as active as a BL Lac jet, albeit observed at a modest offset in the viewing angle ($\sim 10^\circ - 20^\circ$). Such a scenario would also be consistent with the similarity found here between the INOV of RQQs and LDQs, since the latter are already believed to have central engines ejecting relativistic synchrotron jets. Inverse Compton quenching of the jets in a majority of quasars before reaching the scale probed by radio emission (e.g. Brown 1990) could, conceivably, be responsible for the large difference between the radio luminosities of radio-loud and radio-quiet quasars (GSSW03). A possible signature of such quenching is the hard X-ray spectral tail found in some RQQs (George et al. 2000). This emission is seen despite the extremely strong forward flux boosting of the X-rays expected from the inverse Compton scattering of external (e.g. BLR) photons by the relativistic jet ($\propto \delta^{(4-2\alpha)}$, Dermer 1995). In this fashion, radio-loud and radio-quiet quasars can be unified through an orientation based scheme, at least in the realm of intra-night optical variability. This picture is broadly in accord with the idea of *jet-disk symbiosis*, where jets of some type are to be expected from essentially any type of disk (e.g., Falcke, Malkan & Biermann 1995).

7 ACKNOWLEDGMENTS

We thank John McFarland for a helpful discussion. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. G-K is appreciative of hospitality at GSU and is also grateful for support from the ESO senior visitor program during which this programme originated a decade ago. CSS thanks NCRA for hospitality and the use of its facilities. PJW is grateful for hospitality at NCRA and at the Princeton University Observatory. PJW's efforts were partially supported by Research Program Enhancement funds at GSU.

REFERENCES

- Antonucci R. R. J., 1993, ARA&A, 31, 473
 Antonucci R., Barvainis R., Alloin D., 1990, ApJ, 353, 416
 Barthel P. D., 1989, ApJ, 336, 606
 Becker R. H., White R. L., Helfand D. J., 1995, ApJ, 450, 559
 Blandford R., 2000, Phil. Trans. Roy. Soc. London, Sec. A., (astro-ph/0001499)
 Blandford R., Rees M. J., 1978, in Wolfe A. M., ed, Pittsburgh Conference on BL Lac Objects, Pittsburgh U., p. 328
 Blundell K. M., Beasley A. J., 1998, MNRAS, 299, 165
 Blundell K. M., Rawlings S., 2001, ApJ, 562, L5
 Bregman J., 1994, in Courvoisier T. J. L., Blecha A. eds, IAU Symposium 159, Multiwavelength Continuum Emission of AGNs. Reidel, Dordrecht, p. 5
 Brown R. L. 1990, in Zensus, J. A., Pearson, T. J., eds, Parsec-scale Radio Jets. CUP, Cambridge, p. 199
 Carini M. T., 1990, Ph.D. dissertation, Georgia State University
 Carini M. T., Miller H. R., Noble J. C., Goodrich B. D., 1992, AJ, 104, 15
 Carini M. T., Miller H. R., Noble J. C., Sadun A. C., 1991, AJ, 101, 1196
 Cellone S. A., Romero G. E., Combi J. A., 2000, AJ, 119, 1534
 Cid Fernandes C. R., Aretxaga I., Terlevich R., 1996, MNRAS, 282, 1191
 Cirasuolo, M., Magliocchetti, A., Celotti, A., Danese, L., 2003 (astro-ph/0301526)
 Condon J. J., et al., 1998, AJ, 115, 1693
 de Diego J. A., Dultzin-Hacyan D., Ramirez A., Benítez E., 1998, ApJ, 501, 69
 Dermer C. D., 1995, ApJ, 446, L63
 Dunlop, J. S., McLure, R. J., Kuku, M. J., Baum, S. A., O'Dea, C. P., Hughes, D. H., 2003, MNRAS, in press (astro-ph/0108397)
 Falcke H., Malkan M. A., Biermann, P. L., 1995, A&A, 298, 375.
 Falcke H., Patnaik A. R., Sherwood W., 1996, ApJ, 473, L13
 George I. M., et al., 2000, ApJ, 531, 52
 Gopal-Krishna, Sagar R., Wiita P. J., 1993, MNRAS, 262, 963 (Paper I)
 Gopal-Krishna, Sagar R., Wiita P. J., 1995, MNRAS, 274, 701 (Paper II)
 Gopal-Krishna, Gupta A. C., Sagar R., Wiita P. J., Chaubey U. S., Stalin C. S., 2000, MNRAS, 314, 815 (Paper IV)
 Gopal-Krishna, Stalin C. S., Sagar R., Wiita P. J., 2003, ApJ, 586, L25
 Gopal-Krishna, Wiita P. J., 1992, A&A, 259, 109
 Gopal-Krishna, Wiita P. J., Altieri B., 1993, A&A, 271, 216
 Heidt J., Wagner S. J., 1996, A&A, 305, 42
 Heidt J., Wagner S. J., 1998, A&A, 329, 853
 Ho L. C., 2002, ApJ, 564, 120

Hughes P., Aller H., Aller M., 1992, *ApJ*, 396, 469
Ivecić, Z., et al., 2002, *AJ*, 124, 2364
Jang M., Miller H. R., 1995, *ApJ*, 452, 582
Jang M., Miller H. R., 1997, *AJ*, 114, 565
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
Kovalev Y. Y., et al., 1999, *A&AS*, 139, 545
Krishan V., Wiita P. J., 1990, *MNRAS*, 246, 597
Krishan V., Wiita P. J., 1994, *ApJ*, 423, 17
Kukula M. J., Dunlop J. S., Hughes D. H., Rawlings S., 1998, *MNRAS*, 297, 366
Lesch H., Pohl M., 1992, *A&A*, 254, 29
Mangalam A. V., Wiita P. J., 1993, *ApJ*, 406, 420
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
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 L., Peacock J. A., Mead A. R. G., 1990, *MNRAS*, 244, 207
Miller P., Rawlings S., Saunders R., 1993, *MNRAS*, 263, 425
Paltani S., Courvoisier T. J. L., 1994, *A&A*, 291, 74
Papadopoulos P. P., Seaquist E. R., Wrobel J. M., Binette L., 1995, *ApJ*, 446, 150
Petrucci P. O., Chelli A., Henri G., Cruz-González I., Salas L., Mujica R., 1999, *A&A*, 342, 687
Rabbette M., McBreen B., Smith N., Steel S., 1998, *A&AS*, 129, 445
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 (Paper III)
Sagar R., Stalin C. S., Gopal-Krishna, Wiita P. J., 2003, in preparation
Smith A. G., Nair A. D., Clements S. D., 1990, in Miller H. R., Wiita P. J., eds, *Variability of Active Galactic Nuclei*. CUP, Cambridge, p. 52
Sopp H. M., Alexander P., 1991, *MNRAS*, 251, 14P
Stalin C. S., 2002, Ph.D. dissertation, Kumaun University
Stalin C. S., Gopal-Krishna, Sagar R., Wiita P. J., 2003, in preparation
Stoeck 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
Urry, C. M., Padovani, P., 1995, *PASP*, 107, 803
Véron-Cetty M.-P., Véron P., 1998, *ESO Scientific Report No. 18*
Wagner S. J., Witzel A., 1995, *ARA&A*, 33, 163
White R. L., et al., 2001, *ApJS*, 126, 133
Wiita P. J., 1996, in Miller H.R., Webb J.R., Noble J.C., eds, *ASP Conf. Ser. Vol. 110, Blazar Continuum Variability*. ASP, San Francisco, p. 42
Wills B. J., Browne I. W. A. 1986, *ApJ*, 302, 56
Wills B. J., Wills D., Breger M., Antonucci R. R. J., Barvainis R., 1992, *ApJ*, 398, 454
Wilson A. S., Colbert E. J. M., 1995, *ApJ*, 438, 62
Woo J. H., Urry C. M., 2002, *ApJ*, 581, L5
Xie G., Zhou S. B., Dai B. Z., Liang E. W., Li K. H., Bai J. M., Xing S. Y., Liu W. W., 2002, *MNRAS*, 329, 689
Zhang L. Z., Fan J. H., Cheng K. S., 2002, *PASJ*, 54, 159
Zhang X.-H., Bao G., 1991, *A&A*, 246, 21

Table 3. Position and apparent magnitudes of the comparison stars

Source	Star	RA(2000)	Dec(2000)	R	B	
0945+438	S1	09 49 16.72	43 33 35.5	16.0	16.6	
	RQQ(Set 1)	S2	09 49 06.08	43 34 16.3	16.4	18.1
	S3	09 49 23.91	43 35 02.3	16.9	18.1	
2349-014	S1	23 52 08.96	-01 05 09.7	14.2	15.7	
	LDQ(Set 1)	S2	23 52 12.60	-01 03 38.3	14.5	15.3
	S3	23 52 13.47	-01 11 07.9	14.7	16.0	
0514-005	S1	05 16 31.08	-00 27 07.7	15.8	16.0	
	RQQ(Set 2)	S2	05 16 27.30	-00 30 18.9	15.4	15.5
	S3	05 16 44.64	-00 26 46.8	15.7	16.4	
1004+130	S1	10 07 26.91	12 46 09.5	15.4	15.8	
	LDQ(Set 2)	S2	10 07 23.24	12 44 53.9	14.6	15.0
	1252+020	S1	12 55 20.98	01 41 13.9	15.2	15.6
RQQ(Set 3)	S2	12 55 35.53	01 41 06.7	15.4	17.1	
	S3	12 55 33.90	01 45 20.4	15.2	16.1	
	S4	12 55 15.61	01 43 54.9	15.0	15.7	
0134+329	S5	12 55 36.03	01 42 04.4	16.0	16.2	
	S6	12 55 33.14	01 45 01.6	15.4	16.8	
	S1	01 37 48.56	33 09 31.0	15.5	17.2	
LDQ(Set 3)	S2	01 37 51.26	33 07 08.9	15.6	16.3	
	S3	01 37 37.27	33 03 26.5	15.4	16.1	
	S1	11 04 04.42	31 41 25.0	16.8	17.6	
1101+319	RQQ(Set 4)	S2	11 04 13.05	31 41 42.2	16.2	17.2
	S3	11 04 10.46	31 43 52.8	16.4	16.8	
	S4	11 04 14.10	31 44 10.2	15.8	17.8	
1103-006	S5	11 04 30.14	31 37 20.3	16.5	18.1	
	S1	11 06 42.42	-00 56 46.3	15.2	15.5	
	LDQ(Set 4)	S2	11 06 44.58	-00 56 23.7	15.5	15.9
1029+329	S3	11 06 32.47	-00 52 41.8	17.1	19.0	
	CS3	11 06 29.36	-00 52 44.8	14.0	15.2	
	S1	10 32 08.93	32 37 50.7	15.3	17.4	
RQQ(Set 5)	S2	10 31 59.48	32 41 56.1	16.3	16.5	
	S3	10 32 03.52	32 40 19.6	15.8	18.7	
	S4	10 32 07.47	32 37 28.1	15.1	16.3	
0709+370	S5	10 31 57.21	32 39 20.0	15.1	16.3	
	s6	10 32 10.74	32 36 06.4	14.8	15.5	
	S1	07 13 01.95	36 59 59.3	16.0	16.4	
LDQ(Set 5)	S2	07 13 09.80	37 00 35.5	15.8	16.3	
	CS2	07 13 24.12	36 56 47.4	14.4	16.2	
	S3	07 13 04.57	37 01 08.5	15.2	15.7	
0748+294	S1	07 50 57.78	29 18 20.8	15.9	16.8	
	RQQ(Set 6)	S2	07 50 56.95	29 17 51.5	15.7	16.4
	S3	07 51 18.87	29 18 36.6	16.3	16.9	
0350-073	S1	03 52 39.78	-07 11 12.3	14.6	15.5	
	LDQ(Set 6)	S2	03 52 40.55	-07 10 10.1	15.3	15.7
	S3	03 52 28.63	-07 08 17.0	15.4	15.7	
1017+279	S1	10 19 55.67	27 46 09.1	16.1	18.6	
	RQQ(Set 7)	S2	10 19 42.79	27 44 53.2	15.6	16.3
	S3	10 19 41.83	27 45 51.0	15.1	15.8	
0012+305	S4	10 19 54.59	27 46 14.5	15.0	15.6	
	S5	10 19 44.13	27 46 08.6	14.4	14.9	
	S1	00 15 38.18	30 52 15.6	16.9	17.8	
LDQ(Set 7)	S2	00 15 29.85	30 50 38.8	16.6	17.3	
	S3	00 15 23.92	30 52 25.1	16.5	17.3	
	S4	00 15 39.99	30 50 08.2	15.3	16.4	
S5	00 15 16.43	30 52 42.4	15.0	16.8		