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

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ABSTRACT

We present results of a programme of multi-epoch, intranight optical monitoring of a sample of non-blazar-type active galactic nuclei (AGN), which includes seven radio-quiet quasars (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 quasi-stellar objects (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 ∼1 per cent variation over the night. Unambiguous detection of intranight optical variability (INOV) amplitudes in the range 1–3 per cent 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 per cent for RQQs and LDQs, respectively; inclusion of the two cases of probable variations of LDQs would raise the duty cycle to 15 per cent for LDQs. The similarity in the duty cycle and amplitude of INOV for the RQQs and LDQs suggests, first, 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 intranight optical variability of four major classes of powerful AGN, including blazars.

Key words: galaxies: active – galaxies: jets – galaxies: photometry – quasars: general.

1 INTRODUCTION

Multiwavelength 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 intranight time-scales are probed. Optical variability on hour-like time-scales 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 known as blazars, variability is strong in essentially all electromagnetic bands, and is commonly associated with the non-thermal Doppler boosted emission from jets (e.g. Blandford & Rees 1978; Marscher & Gear 1985; Hughes, Aller & Aller 1992; Wagner & Witzel 1995). Intranight variability

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in blazars may well arise from instabilities or fluctuations in the flow of such jets (e.g. Hughes et al. 1992; Marscher, Gear & Travis 1992).

As for RQQs, which follow the radio–far-infrared correlation defined for disc 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 disc 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. Miller, Rawlings & Saunders 1993; Kellermann et al. 1994; Papadopoulos et al. 1995; Blundell & Beasley 1998; Kukula et al. 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 intranight 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 active galactic nuclei (AGN) are the reality and origin of the apparent dichotomy in radio emission of quasi-stellar objects (QSOs). Although it has long been claimed that radio-loud quasars are only a small fraction (10–15 per cent) of all QSOs, an analysis of the FIRST radio survey results (White et al. 2000) 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 Sloan Digital Sky Survey (SDSS) optical surveys found that the dichotomy is real and that radio-loud sources are about 8 per cent 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 radio-loud/radio-quiet (RL/RQ) dichotomy, some of them based on the idea that more rapidly spinning black holes produce powerful relativistic jets (e.g. Wilson & Colbert 1995; Blandford 2000). Other 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 by Gopal-Krishna, Wiita & Altieri (1993). Our subsequent work used the 2.34-m Vainu Bappu telescope of the Indian Institute of Astrophysics, Bangalore; later the 1.04-m Sampurnanand telescope of the State Observatory, Naini Tal, was increasingly employed (Gopal-Krishna, Sagar & Wiita 1993; Gopal-Krishna et al. 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 1998 November through 2002 May 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 comprising seven RQQs and seven LDQs. A brief report on some of these results has been published recently (GSSW03). In a recent paper we reported results for the BL Lac and CDQ components of this programme (Sagar et al. 2004). Additional details can be found in Stalin (2002) and Stalin et al. (2004).

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 time-scales (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 have also made attempts to detect and characterize INOV among radio-quiet AGN (Rabbette et al. 1998; Petrucci et al. 1999) 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; Romero et al. 2002; Xie 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 two or three comparison stars within the CCD frame, as well as keeping the exposure time at around 10 min, is similar to the present work, there are major differences as well. First, in the programme of Rabbette et al. (1998), intranight sampling was usually much sparser, with only a few data points per object per night. This, coupled with their typical rms noise of 4 per cent, raises their microvariability detection threshold to $\sim$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 intranight 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

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	per cent 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 (Section 3.1).

sample of 19 RQ AGN and 11 RL AGN and found INOV in three (16 per cent) of the former and nine (82 per cent) 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: eight 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 six 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 eight RQQs was found to vary down to 1 per cent rms, while nine 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 per cent and only 3 per cent, respectively, from this mixed sample. Here ‘duty-cycle’ is defined as the ratio of the total time of 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 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 six of 30 RQQ monitoring sessions and only five 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 programmes, including ours, in the procedure adopted for observation and analysis. de Diego et al. (1998) observed each source only between three and nine times per night; each such observation consisted of five 1-min exposures of the target field. An INOV analysis was then made through an analysis of variance (ANOVA) procedure which attempts to determine observational errors directly from the scatter in the object minus a reference star for the five points within each set of observations. The other programmes, on the other hand, obtained variations of the degree of significance 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 intranight 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 NRAO VLA Sky Survey (NVSS; Condon et al. 1998) and FIRST (Becker et al. 1995) surveys at 1.4 GHz, and our own Very Large Array (VLA) observations (Stalin et al. 2003) 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 and 22 GHz (Kovalev et al. 1999) or from the NASA/IPAC Extragalactic Database (NED).[1] 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 per cent) known for five of the seven LDQs in our sample (Wills et al.

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[1] URL http://ned.ipac.caltech.edu/

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 Stalin (2002), Sagar et al. 2004 and Stalin et al. 2004.

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 1999 October, when a 1024 × 1024 Tektronix CCD was in use. In each CCD a pixel corresponds to 0.38 × 0.38 arcsec^2, covering a 12 × 12 arcmin^2 field for the larger, and a 6 × 6 arcmin^2 field for the smaller, CCD. Since the sensitivities of the CCDs 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 h per night. For each night only one AGN was monitored, as continuously as possible, and the typical sampling rate was about five 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 two or three comparison stars within about a magnitude of the QSO were simultaneously registered on the CCD frame. This redundancy allowed us to identify and discount any comparison star which itself varied during a given night, and thereby ensured reliable differential photometry of the QSO. This method of differential photometry of the quasar relative to two or three comparison stars registered on the same CCD frame enables one to detect QSO variability of small amplitude, as other sources of errors (such as variation in seeing and sky transparency, possible instrumental effects, etc.) are cancelled to lowest order.

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. (2004).

3.2 Data processing

Preliminary processing of the images, as well as the photometry, was done using IRAF.[2] 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[3] 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

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

Object	Type	Date	N^*	T^* (hr)	INOV status	$C_{\rm eff}$	ψ (per cent)
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
0709+370	LDQ	20.01.01	29	6.5	NV		
		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		
0748+294	RQQ	14.12.98	22	7.6	NV		
		13.01.99	56	8.3	NV		
		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		
0350−073	LDQ	14.11.01	31	6.6	NV		
		15.11.01	26	5.5	NV		
		18.11.01	25	5.7	NV		
1017+279	RQQ	14.03.99	43	7.3	NV		
		14.01.00	33	7.1	NV		
		27.02.00	33	8.1	NV		
0012+305	LDQ	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		

*N is the number of observations per night; T is the length of monitoring.

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

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

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
	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
0134+329	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
1101+319	S1	11 04 04.42	31 41 25.0	16.8	17.6
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
	S5	11 04 30.14	31 37 20.3	16.5	18.1
1103−006	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
	S3	11 06 32.47	−00 52 41.8	17.1	19.0
	S4	11 06 29.36	−00 52 44.8	14.0	15.2
1029+329	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
	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
0709+370	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
	S3	07 13 04.57	37 01 08.5	15.2	15.7
	S4	07 13 24.12	36 56 47.4	14.4	16.2
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
	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
0012+305	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

variance of the DLC of the steadiest pair of comparison stars was adopted; the mean value and standard deviation of the aperture radii used was 4.0 ± 1.3 arcsec. We stress that the DLCs are not sensitive to the exact choice of aperture radius. We note that in this particular method of aperture photometry some of the flux from the objects is probably left out of the aperture, but as we are interested in the magnitude differences of the objects and not their absolute fluxes, it is perfectly adequate as long as the aperture sufficiently exceeds the seeing radius and the QSO dominates its host galaxy.

The B and R magnitudes and colours for each QSO and its comparison star were obtained from the United States Naval Observatory (USNO) catalog[4]; 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 Intranight and internight variability

In Figs 1 and 2 the derived DLCs are presented for the three LDQs and three 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 three-point running averages of the respective original data sequences, taken to improve the signal-to-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. (2004). We note that the error bars shown on the data points in Figs 1–3 are those given by the PHOT algorithm in IRAF; however, these nominal error bars are, for PHOT reductions, actually too small by a factor of $\eta \simeq 1.5$ (Stalin 2002 GSSW03). Thus essentially all of the star–star DLCs are consistent with no stellar variations, and when significant stellar variations are present they are noted in the discussions of individual sources below. We have taken into account this correction factor, η, 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 a statistical criterion similar to that of Jang & Miller (1997) with the added advantage that for each QSO we have DLCs relative 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 weighted by a factor η (see GSSW03). This ratio, C_i, for the ith 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 on a given night. 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 $C_{\mathrm{eff}} > 2.57$, which corresponds to a confidence level in excess of 99 per cent. The criterion for 'probable variable' is $C_{\mathrm{eff}} > 2.00$ which corresponds to a confidence level >95 per cent. The last column of Table 2 gives for each DLC the value of the peak-to-peak variability amplitude, $\psi \equiv [(D_{\max} - D_{\min})^2 - 2\sigma^2]^{1/2}$. Here, D is the differential magnitude, $\sigma^2 = \eta^2 \langle \sigma^2_{\mathrm{err}} \rangle$, with η the factor by which the average of the measurement errors (σ_{err}, as given by the PHOT algorithm) should be multiplied; we find $\eta = 1.50$ (Stalin 2002 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

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[4] http://archive.eso.org/skycat/servers/usnoa

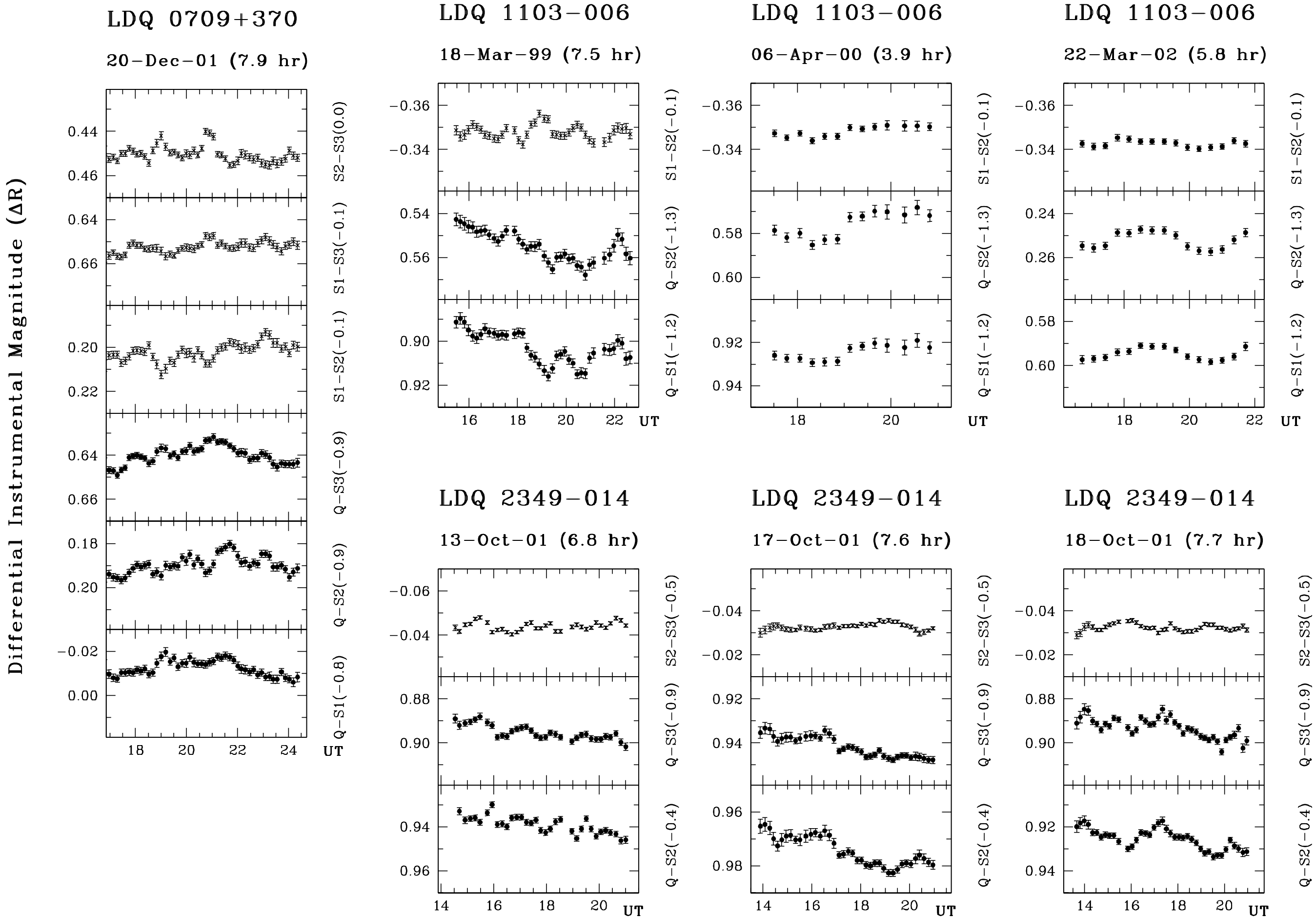

Figure 1. Differential light curves (DLCs) for the radio lobe-dominated quasars (LDQs) with a positive or probable detection of INOV. The name of the quasar, the date and the duration of observations are given at the top of each night's observations. The upper panel(s) give the differential light curves (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.

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 (2000 April 5). By generating a star–star DLC with a large differential colour index $\Delta(B - R) = -1.9$ from the frames taken on the same night of 2000 April 5, 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) intranight 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, but also all the QSOs in our sample are at least an order-of-magnitude more luminous than their putative host galaxies, with the sole exception of the nearby LDQ 2349−014. In this case, the host galaxy is seen on our CCD images; hence, we used a rather large aperture (6-arcsec radius). Moreover, we find that either the seeing disc (as estimated from a star on the CCD frames, which was thus monitored concurrently with the QSO) remained steady, or sharpened slightly during the night, implying that the observed gradual fading of the QSO (Fig. 1) 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 detections 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 per cent over the roughly seven hours of monitoring (Fig. 1). Moreover, between 21.3 UT on 2001 October 17 and 13.5 UT on the next night, the QSO brightened by ~5 per cent (note the different ordinate labels).

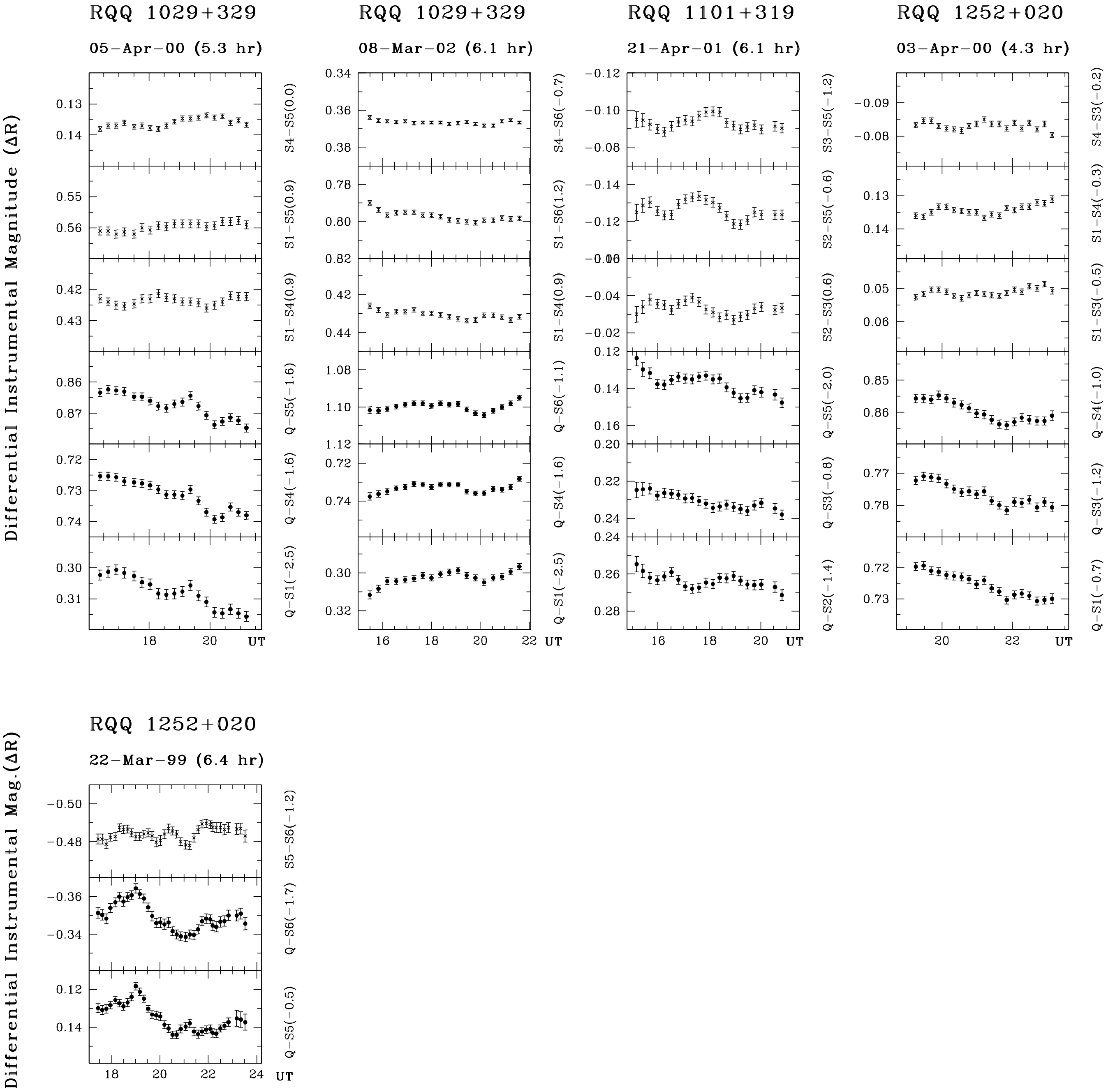

Figure 2. Differential light curves (DLCs) for the radio-quiet quasars (RQQs) for which INOV was detected. The format is identical to that of Fig. 1.

LDQ 1004+130, $z = 0.240$: This QSO was monitored on six nights. In Fig. 3 we present the DLCs for 2001 March 24, which shows a large spike of over 3 per cent ($\sim 9\,\sigma$) at 16.23 UT relative to both available comparison stars, which themselves remained steady. The QSO brightened by ~2 per cent between 20 UT on 2000 March 29 and the observations of the next night which began at 16.0 UT (Stalin 2002; Stalin et al. 2004).

RQQ 1252+020, $z = 0.345$: Over the five nights of monitoring, correlated variability of ~2 per cent amplitude occurred on 1999 March 22 (Fig. 2). On 2000 April 3, the DLCs of the QSO against all three stars showed a gradual fading by ~1 per cent during the 4.1 h 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 2001 April 21. Against all three comparison stars, the QSO flux declined by about 1.5 per cent 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 1999 March 18 show probable INOV, where the LDQ dimmed by about 2 per cent during the first three hours of observations and thereafter remained fairly steady (Fig. 1). On 2000 April 6 there was a probable variation involving an increase

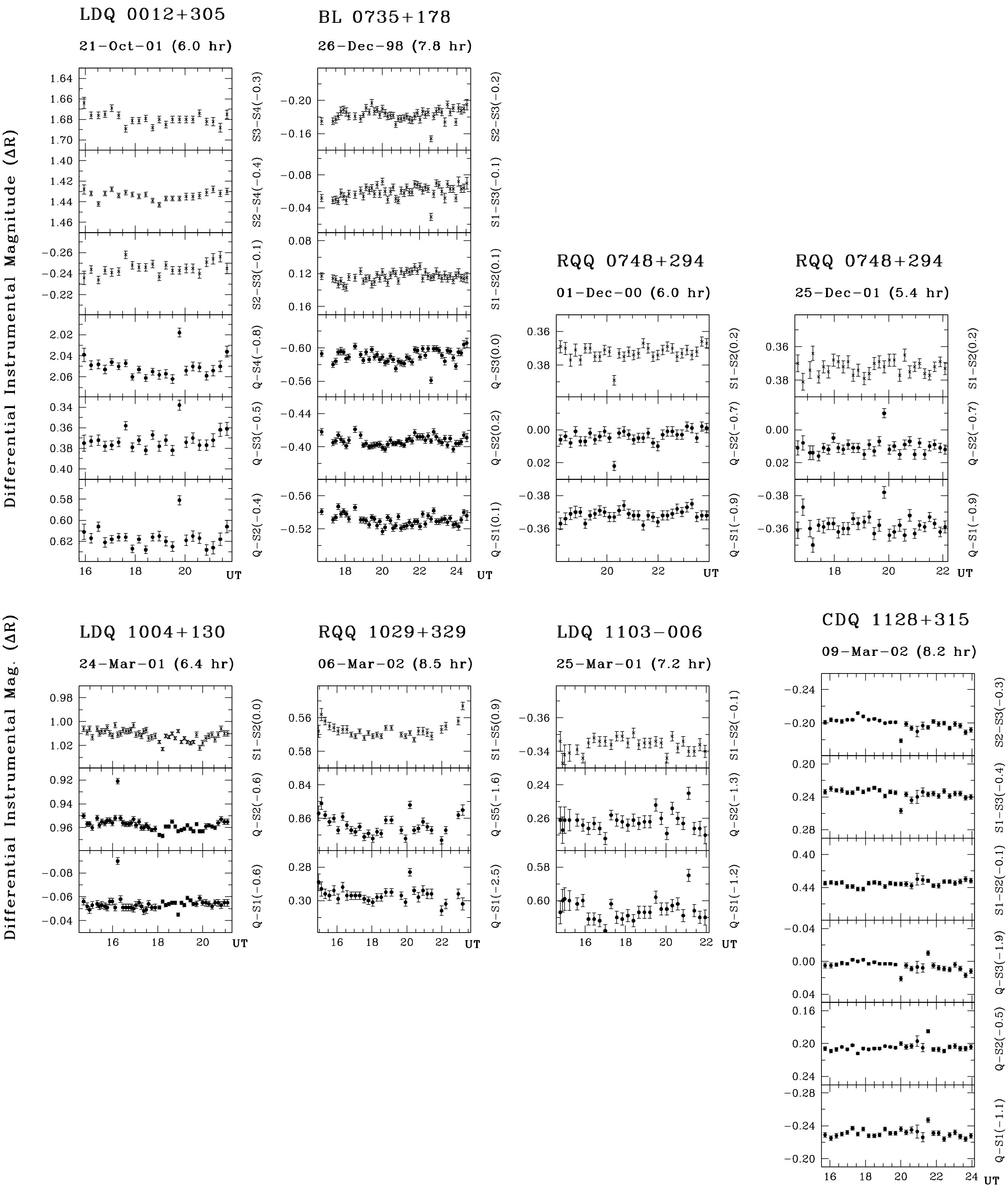

Figure 3. DLCs for the dates on which single-point ‘spikes’ were seen either on the QSO DLC or on the star–star DLC, displayed as in Fig. 1.

in QSO brightness of ∼1 per cent during the ∼4 h of monitoring (Fig. 1). On 2002 March 22, this QSO showed a probable variation (Fig. 1). On 2001 March 25, an apparent variability in the form of a spike of about 2 per cent (∼4 σ) 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 2000 April 5, the QSO slowly dimmed by about 2 per cent against all three stars during the course of the night; the seeing

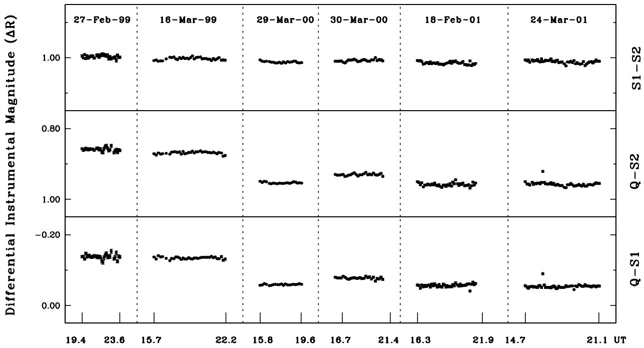

Figure 4. Long-term variations in the DLCs of the LDQ 1004+130, with all star–star and QSO–star DLCs plotted as labelled.

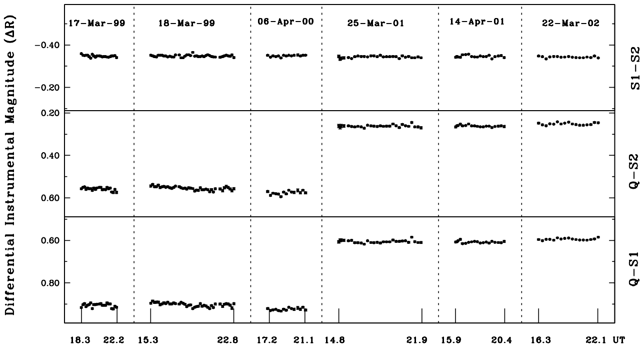

Figure 5. Long-term variations in the DLCs of the LDQ 1103−006, displayed as in Fig. 4.

steadily improved during the night and, if of importance, would have yielded a small gradient opposite to that observed (GSSW03). On 2002 March 8, 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 (2001 March 23 and 2002 March 6) spikes of ∼1.7 per cent (∼3–4σ) were detected (Fig. 3; Stalin et al. 2004).

LDQ 0709+370, $z = 0.487$: On one of the five nights this QSO was monitored, 2001 December 20, the QSO brightened by about 1 per cent against all three comparison stars during the first half of the night and then returned to its initial level during the second half of the night (Fig. 1). Star 2 showed significant variations, but Stars 1 and 3 were steady.

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 2001 December 25 the QSO DLCs showed a ∼2 per cent spike at 19.83 UT (∼4σ) (Fig. 3). Also, a significant star spike was observed at 20.28 UT on 2000 December 1 (star 2 rose by ∼1.8 per cent; 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 per cent ($>4\sigma$) was seen for this QSO at 19.78 UT on 2001 October 21 (Fig. 3).

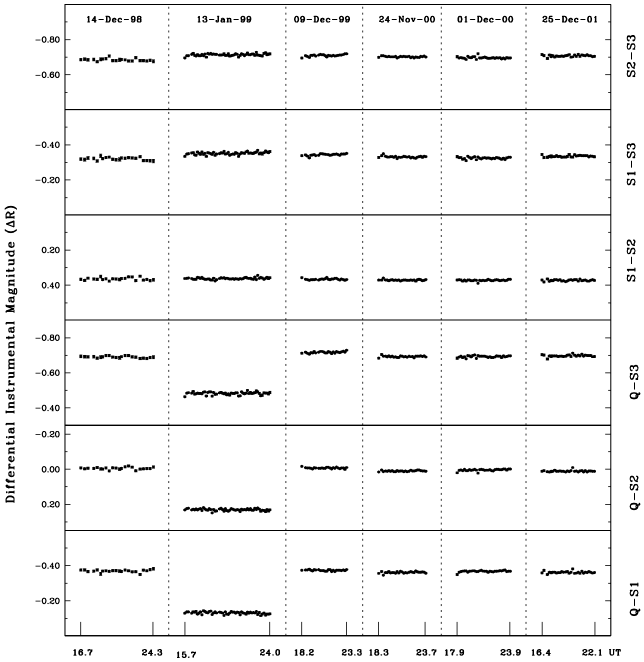

Figure 6. Long-term variations in the DLCs of the RQQ 0748+294, displayed as in Fig. 4.

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 2000 February 26 and 2001 January 23 this QSO was found to have dimmed by about 0.07 mag.

LDQ 1004+130, $z = 0.240$: A drop of 0.09 mag was observed between 1999 March 16 and 2000 March 29. 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 five nights over a three-year period beginning 1999 March 22. It brightened by 0.18 mag between 2000 April 3 and 2001 April 26, and had faded by 0.10 mag at the time of the last observation on 2002 March 18.

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

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

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

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

5 DISCUSSION

5.1 Intranight optical variability (INOV)

In Section 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 per cent, while for X-ray-selected blazars this duty cycle was 28 per cent and for radio-selected quasars (including blazars) 72 per cent, which is comparable to the estimates (over 80 per cent) 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-h duration of monitoring would be ~25 per cent.

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 h per night over 29 nights, while for LDQs it was 5.9 ± 1.5 h per night over 32 nights. Thus it is possible to compare the INOV duty cycles directly 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,

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

where $\Delta\, t_i = \Delta t_{i,\mathrm{obs}} (1+z)^{-1}$ is the duration (corrected for cosmological redshift) of the ith 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 DC = 17 per cent. 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 (Section 2).

Turning to LDQs, we find a DC of 9 per cent for a clear detection of INOV. An additional possible contribution of 6 per cent comes from the two cases of probable detection. So the DC including all likely INOV for the LDQs is about 15 per cent. 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 ($\psi < 3$ per cent) (Table 2; Section 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 ($\psi < 3$ per cent) 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 programme 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 programme, 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 scalelengths) 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 we now explore this point further, taking a clue from the BL Lac object OJ287 monitored in our programme.

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 frame of the observer. 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):

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

Here $p = 3 - \alpha$ for a moving disturbance or blob in the jet; the spectral index of the emission is $\alpha \equiv \mathrm{d}\ln(S_\nu)/\,\mathrm{d}\ln(\nu)$, 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 $\Delta t_{\mathrm{obs}} = \Delta t_{int}(1+z)\,/\,\delta$.

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 (~5 per cent) and rapid (~0.8 h) variation on 2000 March 28 (Stalin 2002; Sagar et al. 2004). For this source, $\delta_{\mathrm{o}} = 14.88$ 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 an observer at a larger viewing angles to the jet, by mapping the observed DLC on to the 'amplitude–time' plane corresponding to chosen values of δ. This mapping is achieved simply by compressing the observed DLC amplitudes by a factor $(\delta/\delta_{\mathrm{o}})^p$ and, simultaneously, stretching the DLCs along the time axis by a factor $(\delta_{\mathrm{o}}/\delta)$, 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 $\theta = 3\overset{\circ}{.}75$ for the jet of OJ 287, the estimated $\delta_{\mathrm{o}} = 14.88$ corresponds to $\beta = 0.9966$. This would give $\delta = 10$ for a modestly misaligned jet with $\theta \simeq 6^\circ$, $\delta = 7$ for $\theta \simeq 7\overset{\circ}{.}5$ 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 ~10° show barely detectable INOV, as is indeed observed for both LDQs and RQQs (Figs 1 and 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 somewhat more misdirected) as those in BL Lacs (GSSW03). 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).

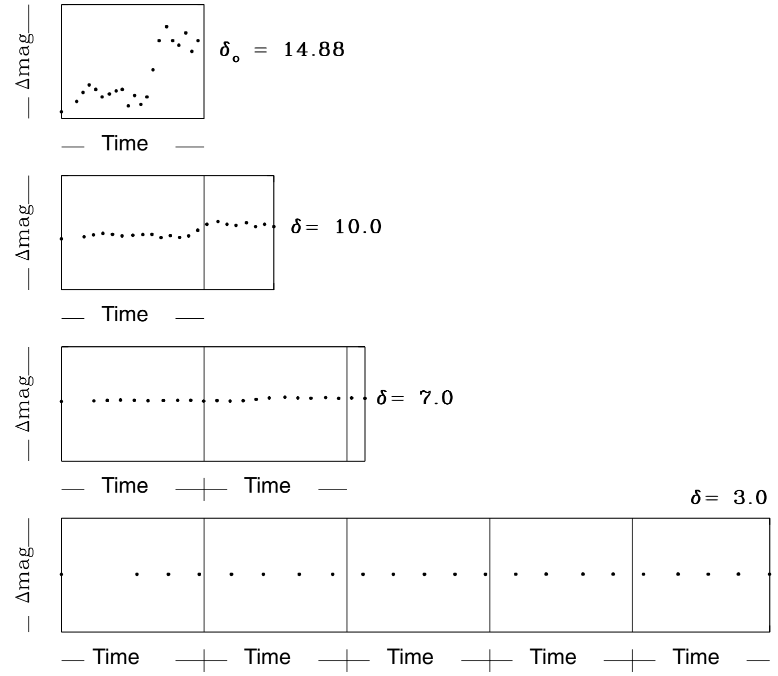

Figure 7. The top panel presents the *R*-band light curve of the BL Lac object 0851+202 (OJ 287), showing a ∼5 per cent fluctuation, observed on 2000 March 28. Subsequent panels show its translation to progressively smaller Doppler factors, corresponding to larger viewing angles, assuming the model of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

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 fluctuation in the entire data set, including the DLCs of CDQs and BL Lacs that are reported in detail elsewhere (Stalin 2002; Stalin et al. 2004). 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 (with σ corrected by the factor of $\eta = 1.5$, Section 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 four types) and 20 spikes associated with their comparison stars. Since we typically derive DLCs for two or three 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 Star 3 in the field of the LDQ 0709+370 on 2001 January 20 at 18.19 UT where a negative deviation of ∼1.7 per cent ($>5\sigma$) was found.

A single stellar spike in Star 2 for RQQ 0748+294, plotted in Fig. 3, was mentioned above (Section 4.1). 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 2002 March 9 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. (2004).

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 *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 μJy) 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

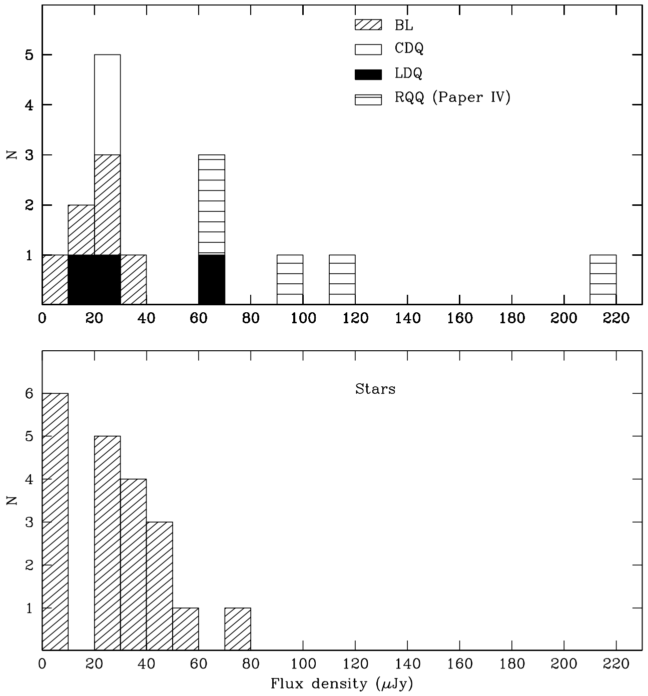

Figure 8. Histogram of flux densities of the 'spikes' detected in both the current programme and those reported in Paper IV. The lower panel gives the distribution of fluxes for the spikes seen in the DLCs between the comparison stars and the upper panel shows the same as seen in the DLCs between the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

be important (e.g. Krishan & Wiita 1990; Krishan & Wiita 1994; Lesch & Pohl 1992; 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, Nair & Clements 1990; Hook et al. 1994; Cristiani et al. 1996; Cristiani et al. 1997) nearly all QSOs which we monitored over 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 Section 4.2. In addition, the LDQ 0709+370 showed a variation of about 3 per cent between 2001 January and December.

The only object not observed to have varied over month/year time-scales 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 four days and six 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 time-scales to be obtained, we must remark upon the peculiar behaviour of the RQQ 0748+294 ($z = 0.910$) which was rather evenly sampled between 1998 December and 2001 December (Fig. 6). For the first and for the last four measurements this object showed a constant brightness to within 1 per cent, but on the night of 1999 January 13 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 disc at roughly 100 Schwarzschild radii from a $10^8\ \mathrm{M}_\odot$ putative central black hole could block a significant fraction of the optical continuum emission from the inner portion of the disc for some months.

In our small sample, there is no obvious difference in the behaviour of RQQs and LDQs in terms of optical variability on month-to-year time-scales. This is in accord with the conclusions reached by Paltani & Courvoisier (1994) from their study of *International Ultraviolet Explorer* data for radio-loud and radio-quiet QSOs in the ultraviolet. Our sample is too small, and the time spanned by our observations is too short, to address any statistical correlations, such as the indications that more luminous QSOs show less variability, while higher-redshift objects show more variability in their rest-frames (Cristiani et al. 1996; Cristiani et al. 1997).

6 CONCLUSIONS

The observations reported here in detail have further reinforced the evidence for the phenomenon of optical intranight variability of optically luminous quasars of non-blazar type (both radio-quiet and lobe-dominated; also see GSSW03). The dense temporal sampling over long durations, 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 time-scales of hours are real. Even though the percentage luminosity 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, Aretxaga & Terlevich 1996) untenable for these rapid events.

Although our full programme covered BL Lacs and CDQs as well (see, GSSW03; Sagar et al. 2004; Stalin et al.2004), in this paper we have provided results for a subsample of seven RQQs and seven 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 observe such events simultaneously 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 1999 January 13 is due to partial occultation of the optical continuum source, perhaps by a non-axisymmetric disc deformation.

While our data cannot exclude accretion disc flares as the source of the much milder and rarer intranight optical variability observed for RQQs and LDQs, as compared to BL Lacs (Section 1), it does not preclude a substantial contribution to this type of flux variability coming from blazar-like relativistically beamed emission. In Section 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$10–20°). Such a scenario would also be consistent with the similarity found here between the INOV of RQQs and LDQs, since the latter are already believed to have central engines ejecting relativistic synchrotron jets. Inverse Compton quenching of the jets in a majority of quasars before reaching the scale probed by radio emission (e.g. Brown 1990) could, conceivably, be responsible for the large difference between the radio luminosities of radio-loud and radio-quiet quasars (GSSW03). A possible signature of such quenching is the hard X-ray spectral tail found in some RQQs (George et al. 2000). This emission is seen despite the extremely strong forward flux boosting of the X-rays expected from the inverse Compton scattering of external (e.g. broad line region) photons by the relativistic jet ($\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 intranight optical variability. This picture is broadly in accord with the idea of jet–disc symbiosis, where jets of some type are to be expected from essentially any type of accretion disc (e.g. Falcke, Malkan & Biermann 1995).

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