

# Optical variability of radio-intermediate quasars

Arti Goyal,<sup>1\*</sup> Gopal-Krishna,<sup>2</sup> S. Joshi,<sup>1</sup> R. Sagar,<sup>1</sup> Paul J. Wiita,<sup>3,4</sup> G. C. Anupama<sup>5</sup>  
and D. K. Sahu<sup>5</sup>

<sup>1</sup>*Aryabhata Research Institute of Observational Sciences (ARIES), Manora Peak, Nainital 263 129, India*

<sup>2</sup>*National Centre for Radio Astrophysics/TIFR, Pune University Campus, Pune 411 007, India*

<sup>3</sup>*School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540, USA*

<sup>4</sup>*Department of Astronomy and Physics, Georgia State University, Atlanta, GA 30303, USA*

<sup>5</sup>*Indian Institute of Astrophysics (IIA), Bangalore 560 034, India*

Accepted 2009 October 8. Received 2009 October 7; in original form 2009 August 11

## ABSTRACT

We report the results of our intensive intranight optical monitoring of eight optically bright ‘radio-intermediate quasars’ (RIQs) having flat or inverted radio spectra. The monitoring was carried out in *R* band on 25 nights during 2005–2009. On each night only one RIQ was monitored for a minimum duration of  $\sim 4$  h (the average being 5.2 h per night). Using the CCD as an N-star photometer, an intranight optical variability (INOV) detection threshold of  $\sim 1$ –2 per cent was achieved for the densely sampled differential light curves derived from our data. These observations amount to a large increase over those reported hitherto for this rare and sparsely studied class of quasars which can, however, play an important role in understanding the link between the dominant varieties of powerful active galactic nucleus, namely the radio-quiet quasars (RQQs), radio-loud quasars (RLQs) and blazars. Despite the probable presence of relativistically boosted nuclear jets, inferred from their flat/inverted radio spectra, clear evidence for INOV in our extensive observations was detected only on one night. Furthermore, flux variation between two consecutive nights was clearly seen for one of the RIQs. These results demonstrate that as a class, RIQs are much less extreme in nuclear activity compared to blazars. The availability in the literature of INOV data for another two RIQs conforming to our selection criteria allowed us to enlarge the sample to 10 RIQs (monitored on a total of 42 nights for a minimum duration of  $\sim 4$  h per night). The absence of large amplitude INOV ( $\psi \geq 3$  per cent) persists in this enlarged sample. This extensive data base have enabled us to arrive at the first estimate for the INOV duty cycle (DC) of RIQs. The DC is found to be small ( $\sim 9$  per cent), increasing to  $\sim 14$  per cent if the two cases of ‘probable’ INOV are included. The corresponding value is known to be  $\sim 60$  per cent for BL Lacs and  $\approx 15$  per cent for both RLQs and RQQs, if they too are monitored for  $\gtrsim 4$ –6 h in each session. Our observations also provide information about the long-term optical variability of RIQs, which is found to be fairly common and reaches typical amplitudes of  $\approx 0.1$  mag. The light curves of these RIQs are briefly discussed in the context of a theoretical framework proposed earlier for linking this rare kind of quasars to the much better studied dominant classes of quasars.

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

## 1 INTRODUCTION

Although sparsely studied so far, radio-intermediate quasars (RIQs) can serve as an important tool for probing the relationship between the radio-loud quasars (RLQs), blazars and radio-quiet quasars

(RQQs, also termed as radio weak quasars). Ever since the discovery of quasars, the dichotomy in their radio loudness has been debated as an outstanding issue, since about  $\sim 10$  per cent of optically selected quasars are found to be stronger emitters in the radio band compared to the remaining population (Sandage 1965; Strittmatter et al. 1980; Kellermann et al. 1989, 1994; Stocke et al. 1992). Following Kellermann et al. (1989) who made Very Large Array (VLA) observations of optically selected Palomar–Green Bright Quasar Survey

\*E-mail: arti@aries.res.in

(BQS) objects, radio loudness is usually quantified in terms of a parameter ‘ $R$ ’, the ratio of continuum flux density at radio (5 GHz) and optical (4400 Å) wavelengths. The histogram of  $R$  found in their study shows a large peak at  $R \lesssim 0.1$ –3 and a second, weaker peak at  $R \sim 100$ –1000. Accordingly, quasars falling in the range  $3 < R < 100$  can be termed as ‘radio-intermediate quasars’ (e.g. Miller, Rawlings & Saunders 1993; see also Diamond-Stanic et al. 2009). Although it has been argued that RLQs are merely the tail of a broad distribution of quasar radio strengths and not a separate population (e.g. Cirasuolo et al. 2003) careful analysis of the largest available samples strongly indicates that there is indeed a bimodal distribution in  $R$  (Ivezić et al. 2002, 2004) and that the radio-loud fraction increases with rising optical luminosity but decreases with increasing redshift (e.g. Jiang et al. 2007; Rafter, Crenshaw & Wiita 2009).

The observed radio luminosity of a RIQ is typically well above the value dividing the Fanaroff–Riley type I (FRI) and type II (FR II) radio galaxies [ $\log P_{20\text{cm}} (\text{W Hz}^{-1}) \simeq 25.0$ ] (Falcke, Gopal-Krishna & Biermann 1995b), but probably not so once the possibility of relativistic flux boosting is taken into account (e.g. Wang et al. 2006). It has been long been suggested that RIQs are Doppler boosted counterparts of RQQs, such that the relativistic jet is closely aligned to the line of sight. This was mainly inferred from the radio versus [O III] line intensity diagram for optically selected quasars and also from the high brightness temperature of the radio emission from RIQs, as well as their usually flat or inverted radio spectra and substantial radio flux variability (Miller et al. 1993; Falcke, Gopal-Krishna & Biermann 1995b; Falcke, Patnaik & Sherwood 1996b; Xu, Livio & Baum 1999; cf. Falcke et al. 2001; Barvainis et al. 2005).

Implicit in this paradigm is the presence of relativistic jets in RQQs. This premise has received considerable support from deep radio imaging, which has revealed faint kpc-scale radio structures in several RQQs (e.g. Kellermann et al. 1994; Blundell & Rawlings 2001; Leipski et al. 2006). In addition, Blundell, Beasley & Bicknell (2003) have reported evidence for a highly relativistic parsec scale radio jet in the RQQ PG 1407+263. Independent support for the possibility of RQQs possessing relativistic jets has come from the observations of intranight optical microvariability in RQQs (e.g. Gopal-Krishna, et al. 2000; Gopal-Krishna et al. 2003; Gupta & Joshi 2005; Czerny et al. 2008) and in their weaker cousins, Seyfert 1 galaxies (Jang & Miller 1995, 1997; Carini, Noble & Miller 2003). At least a modest amount of relativistic beaming in the jets of radio weak quasars has also been inferred from the detection of compact cores on very long baseline interferometry (VLBI) scales and radio variability on month-like to year-like time-scales, indicating minimum brightness temperatures in a broad range from  $10^8$  to  $10^{11}$  K (e.g. Barvainis et al. 2005; Ulvestad, Antonucci & Barvainis 2005; Wang et al. 2006). However, there is at present little clarity about the nature of jets in RQQs vis-à-vis those in RLQs and blazars whose jets are widely attributed to spinning supermassive black holes (SMBHs; Blandford 1990 and references therein; Wilson & Colbert 1995), or more massive SMBHs accreting at smaller fraction of the Eddington rate (e.g. Boroson 2002). A number of authors have drawn an analogy between the radio emission of quasars and X-ray binaries and have attributed the main difference between RLQs and RQQs to different accretion modes changing the nature of their jets (e.g. Körding, Jester & Fender 2006). Stellar mass black holes are known to slide into a state where radio emission is strongly suppressed or quenched (e.g. Corbel et al. 2001; Maccarone, Gallo & Fender 2003). In this general picture RIQs could well be relativistically beamed counterparts of the RQQ jets. In alternative schemes, the radio weakness of RQQs is attributed to

a rapid deceleration of the jet on subparsec scale, caused perhaps by the following: strong interaction with the torus material (e.g. Falcke, Malkan & Biermann 1995a; Falcke et al. 1995b); mass loading with the debris of stars tidally disrupted by the SMBH (Gopal-Krishna, Mangalam & Wiita 2008); ejection velocities less than the escape velocity (Ghisellini, Haardt & Matt 2004) or a high photon density environment produced by the quasar (Barvainis et al. 2005).

If indeed, RIQs are relativistically boosted counterparts of RQQs, observing the former provides an opportunity to better detect RQQ jets and compare their properties with the better studied, more powerful radio jets of RLQs. For instance, it would be interesting to enquire if the postulated relativistic beaming of RQQ jets manifests itself as blazar-like behaviour in RIQs. Indeed, this seems to be the case for the most prominent example of the RIQ class, namely III Zw 2 (see below). However, essentially no such information is currently available for RIQs as a class even though they, despite being numerically rare, are a potentially very important link between the major active galactic nucleus (AGN) classes powered by nuclear activity, namely RQQs, RLQs and blazars. The present study is a first attempt to bridge this gap in a statistically significant manner.

In terms of radio properties, RIQs form a distinct subclass. Their dominant feature is a radio core (compact on arcsecond scale) of a flat, variable radio spectrum (Falcke et al. 1996b; Kukula et al. 1998; also see Kellermann et al. 1994; Ulvestad et al. 2005). The aforementioned view that they are relativistically boosted RQQ jets has found strong support from the discoveries of long-term, large amplitude (up to a factor of 20) radio variability of the RIQ III Zw 2 (B0007+106; Teräsranta et al. 1998) and of superluminal motion in its radio core (Brunthaler et al. 2000, 2005), both being canonical attributes of blazars. Unfortunately, equivalent observational data are severely lacking for other known RIQs. It may further be emphasized that III Zw 2 ( $z = 0.089$ ) has in fact been classified as Seyfert 1 (Arp 1968; Osterbrock 1977) hosted by a spiral galaxy (Hutchings & Campbell 1983; Taylor et al. 1996). Thus, an interesting question is which, if any, blazar-like characteristics are associated with RIQs of high optical luminosity ( $M_B < -23.5$ ), which are bona fide quasi-stellar objects (QSOs) and hence more likely to be associated with massive elliptical galaxies. Promising indications come from the recent finding that for the radio spectra of the RIQs found in the Sloan Digital Sky Survey (SDSS) are typically flat or inverted (consistent with the postulated relativistic beaming of their jets) and, moreover, radio flux variability (near 1 GHz) on year-like time-scales is actually comparably common for RIQs and RLQs (Wang et al. 2006). For both these reasons, RIQs appear to be promising candidates for intranight optical variability (INOV), albeit it is unclear if the mechanism responsible for long-term variations is also responsible for INOV.

In recent years, INOV has been increasingly recognized as a signature of blazar-like jets. Extensive observations have shown that INOV with large amplitude (with variations,  $\psi$ , exceeding 3 per cent) occurs almost exclusively in blazars and, furthermore, the duty cycle (DC) of INOV in blazars is very high ( $> 50$  per cent), provided the monitoring duration exceeds about 4 h (e.g. Carini 1990; Gopal-Krishna et al. 2003; Stalin et al. 2004a, 2005). To exploit this clue we have carried out an INOV survey of a fairly large and representative sample of eight RIQs, further augmented by the INOV data available in the literature for another two RIQs that meet the selection criteria adopted for our sample of eight RIQs. Thus, the enlarged sample consists of 10 optically bright and intrinsically luminous, core-dominated RIQs. Considerable evidence exists for relativistic beaming in these RIQs. Falcke et al. (1995a) find J1336+1725 to be radio variable, but not J1701+5149. For

**Table 1.** Sample of 10 RIQs used in the present study.

IAU name (1)	RA (J2000) (2)	Dec. (J2000) (3)	$B$ (4)	$M_B$ (5)	$z$ (6)	$P_{\text{op}}^{\ddagger}$ (per cent) (7)	$P_{5\text{GHz}}^{\S}$ (8)	$\alpha_{\text{radio}}$ (9)	$\log R^{*\dagger}$ (10)	References (11)
J0748+2200*	07 48 15.4	+22 00 59.6	17.18	−27.2	1.059	–	$2.9 \times 10^{25c}$	–	1.106	(1)
J0832+3707*	08 32 25.3	+37 07 36.7	16.61	−22.1	0.091	–	$1.1 \times 10^{23c}$	−0.50	1.142	(1)
J0836+4426*	08 36 58.9	+44 26 02.4	15.09	−25.9	0.249	–	$1.7 \times 10^{24c}$	+0.14	0.422	(1)
J0907+5515*	09 07 43.6	+55 15 12.5	17.81	−25.2	0.645	–	$2.4 \times 10^{25c}$	–	1.788	(1)
J1259+3423*	12 59 48.7	+34 23 22.8	17.05	−28.0	1.375	0.65 <sup>a</sup>	$6.0 \times 10^{25c}$	+0.06	1.090	(2)
J1312+3515	13 12 17.7	+35 15 20.8	15.64	−24.6	0.184	0.31 <sup>b</sup>	$2.7 \times 10^{24d}$	0.00‡	1.312	(3)
J1336+1725*	13 36 01.9	+17 25 14.0	16.23	−26.5	0.554	0.18 <sup>b</sup>	$2.7 \times 10^{25e}$	−0.31‡	1.330	(3)
J1539+4735*	15 39 34.8	+47 35 31.0	15.81	−27.7	0.772	0.90 <sup>b</sup>	$2.6 \times 10^{25e}$	+0.19‡	1.439	(3)
J1701+5149	17 01 25.0	+51 49 20.0	15.49	−25.8	0.292	0.54 <sup>b</sup>	$1.1 \times 10^{23f}$	−0.2*	0.914	(3)
J1719+4804*	17 19 38.3	+48 04 13.0	14.60	−29.8	1.083	0.40 <sup>b</sup>	$2.6 \times 10^{26g}$	+0.49‡	0.863	(3)

<sup>¶</sup>References for the optical polarization: <sup>a</sup>Stockmann, Moore & Angel (1984); <sup>b</sup>Berriman et al. (1990).

<sup>§</sup>The radio luminosity at 5 GHz (W/Hz/Sr) is calculated using high-resolution fluxes available from the literature. The references are <sup>c</sup>Becker, White & Helfand (1995); <sup>d</sup>Falcke et al. (1996b); <sup>e</sup>Kellermann et al. (1989); <sup>f</sup>Blundell & Beasley (1998); <sup>g</sup>Helmboldt et al. (2007). If measurements were at a different frequency, then the luminosities were converted into 5 GHz luminosities assuming the core spectral index  $\alpha_C = 0.0$  ( $S_\nu \propto \nu^\alpha$ ) wherever the spectral index of the source was not known.

<sup>†</sup> $R^*$  is the  $K$ -corrected ratio of the 5 GHz to 2500 Å flux densities (Stocke et al. 1992); references for the radio fluxes are Véron-Cetty & Véron (2006), NVSS (Condon et al. 1998) and FIRST (Becker et al. 1995).

\*From Kukula et al. (1998) using observations of the core at 8.4 and 4.8 GHz.

‡From Falcke et al. (1996a) which were derived using the quasi-simultaneous observations at 2.7 and 10.0 GHz with  $S_\nu \propto \nu^\alpha$  while the remainder have been calculated using non-simultaneous observations available in NED.

Reference in column (11): (1) Wang et al. (2006); (2) Carini et al. (2007); (3) Falcke et al. (1996a).

J1259+3423 multi-epoch flux measurements are not known to us, hence its variability status is unknown at present. The remaining seven RIQs in our sample are all found to be radio variable (Falcke, Sherwood & Patnaik 1996a; Wang et al. 2006). Thus, at least eight of the 10 RIQs are known to shown radio variability. Furthermore, spectral information is available in the literature for eight out of the 10 RIQs and each case the radio spectrum is found to be either flat or inverted (see Table 1). All this suggests that the radio jets in essentially all these RIQs are at least modestly Doppler boosted.

## 2 THE RIQ SAMPLE

Since detection of any blazar-like jet characteristics in RIQs is our main objective here, we have focused on the RIQs for which credible evidence for relativistically boosted jet emission exists (at least in the radio band). This leads us to largely excluding the steep-spectrum RIQs, which also exist (e.g. Martíneze et al. 2006). Thus, our sample contains only RIQs having flat or inverted radio spectra (at least a flat-spectrum radio core), in addition to satisfying the usual criterion, namely,  $K$ -corrected ratio  $R^*$  of 5 GHz to 2500 Å fluxes, falling in the range  $3 < R^* < 100$  (Section 1; Miller et al. 1993). Moreover, in order to attain an INOV detection threshold of  $\sim 1$ –2 per cent using a 1–2 m class telescope equipped with a CCD detector, we have confined ourselves to optically bright RIQs ( $m_B < 18.0$  mag). Finally, in order to minimize contamination from the host galaxy (Cellone, Romero & Combi 2000), our sample was restricted to intrinsically luminous AGNs with  $M_B < -23.5$  mag (see also Stalin et al. 2004a). Based on these well-defined basic criteria, our sample (Table 1) was assembled in the following manner.

(a) Seven RIQs with adequate brightness and good nearby comparison stars originally were selected from the list of 89 RIQs prepared by Wang et al. (2006) based on the detection of radio flux variability among SDSS quasars; they are thus presumed to have a flat/inverted radio spectrum. Out of these, three RIQs (J140730.43+545601.6, J162548.79+264658.7 and J210757.67−062010.6) could not be monitored due to observing time constraints, leaving the remaining four RIQs in our sample.

(b) Four RIQs were chosen from table 1 of Falcke et al. (1996a) on the criterion of having a flat/inverted radio spectrum, based on their quasi-simultaneous measurements at 2.7 and 10 GHz ( $\alpha > -0.5$ ;  $S_\nu \propto \nu^\alpha$ ).

(c) One RIQ (J1259+3423) was contributed by the sample observed by Carini et al. (2007).

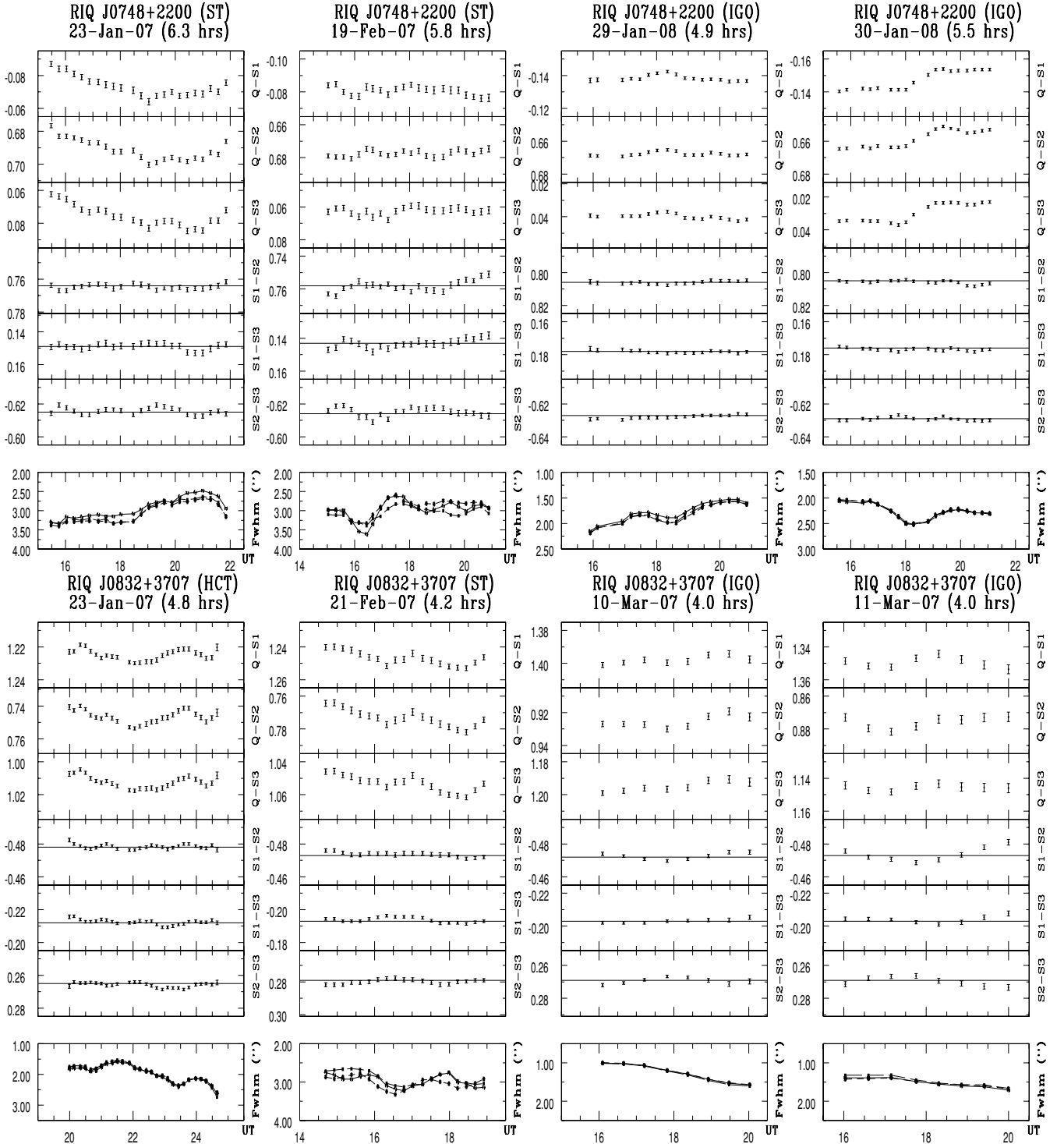
(d) One RIQ (J1701+5149) was included in our sample, despite its being reported as a steep-spectrum type (Falcke et al. 1996a), because it was later resolved and found to possess a core with a flat spectrum, with  $\alpha_{4.8}^{8.4} \simeq -0.2$  (Kukula et al. 1998; see also Hutchings, Neff & Gower 1992).

Lastly, we note that the RIQ J0832+3707 is included in the our sample in spite of its being nearly 1-mag fainter than the adopted threshold ( $M_B < -23.5$  mag), since it is found to be stellar in the FIRST Bright Quasar Survey (FBQS) (White et al. 2000). However, its exclusion from the sample would have no significant impact on our conclusions. Table 1 lists our sample of 10 RIQs. Columns are as follows: (1) source name (an asterisk indicates that the source was monitored by us); (2) right ascension; (3) declination; (4) apparent  $B$  magnitude; (5) absolute  $B$  magnitude; (6) redshift; (7) optical polarization; (8) radio luminosity at 5 GHz; (9) radio spectral index; (10) radio loudness parameter  $R$  computed by us; (11) reference code. We have used a concordance cosmology with Hubble constant  $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_M = 0.27$  and  $\Omega_\Lambda = 0.73$  (Komatsu et al. 2009) and compute the luminosity distance using Hogg (1999).

## 3 OBSERVATIONS

### 3.1 Instruments used

The observations were mainly carried out using the 104-cm Sampurnanand telescope (ST) located at Aryabhata Research Institute of Observational Sciences (ARIES), Nainital, India. It has a Ritchey–Chretien (RC) optics with a  $f/13$  beam (Sagar 1999). The detector was a cryogenically cooled  $2048 \times 2048$  chip mounted at the Cassegrain focus. This chip has a readout noise of  $5.3 \text{ e}^- \text{ pixel}^{-1}$



**Figure 1.** The intranight optical DLCs of the RIQs monitored in the present study. For each night, the source, the telescope used, the date and the duration of monitoring are given. The upper three panels show the DLCs of the source relative to three comparison stars while the attached lower three panels shows the star–star DLCs, where the solid horizontal lines mark the mean for each steady star–star DLC. The bottom panel gives the plots of seeing variation for the night, based on three stars monitored along the RIQ on the same CCD frame.

and a gain of  $10e^-$  Analog to Digital Unit $^{-1}$  (ADU) in the usually employed slow readout mode. Each pixel has a dimension of  $24 \mu\text{m}^2$ , corresponding to  $0.37 \text{ arcsec}^2$  on the sky, thereby covering a total field of  $13 \times 13 \text{ arcmin}^2$ . We carried out observations in a  $2 \times 2$  binned mode to improve the signal-to-noise (S/N) ratio. The seeing usually ranged between  $\sim 1.5$  and  $\sim 3.0 \text{ arcsec}$ , as determined

using three fairly bright stars on the CCD frame; plots of the seeing are provided for all of the nights in the bottom panels of Fig. 1 (see Section 4).

Some of the observations were carried out using 200-cm IUCAA Girawali Observatory (IGO) telescope located at Girawali, Pune, India, which is a RC design with a  $f/10$  beam at the Cassegrain

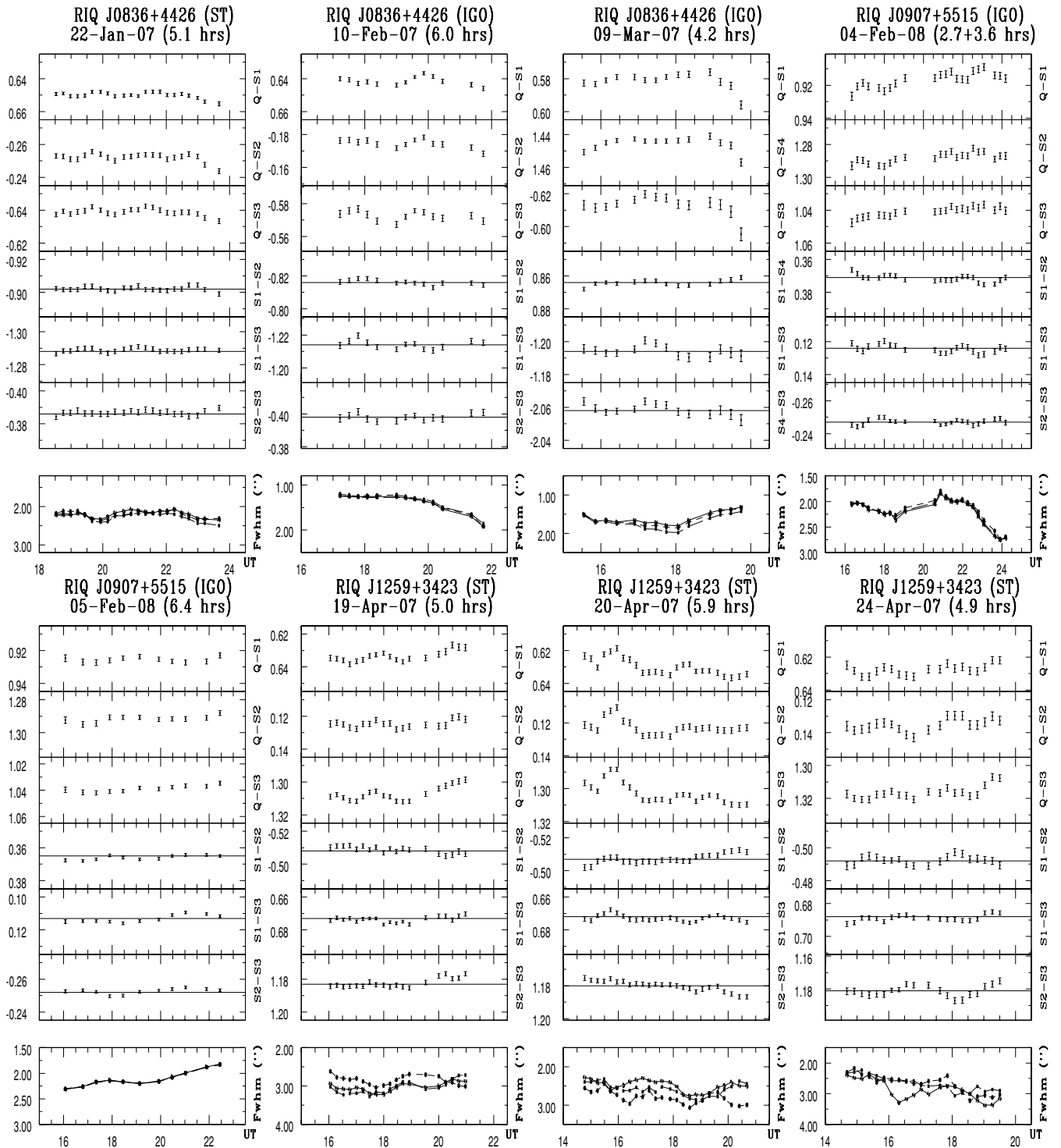


Figure 1 – continued

focus.<sup>1</sup> The detector was a cryogenically cooled  $2110 \times 2048$  chip mounted at the Cassegrain focus. The pixel size is  $15 \mu\text{m}^2$  so that the image scale of  $0.27 \text{ arcsec pixel}^{-1}$  covers an area on  $10 \times 10 \text{ arcmin}^2$  on the sky. The readout noise of CCD is  $4.0 \text{ e}^- \text{ pixel}^{-1}$  and the gain is  $1.5 \text{ e}^- \text{ ADU}^{-1}$ . The CCD was used in an unbinned mode. The seeing ranged mostly between  $\sim 1.0$  and  $\sim 3.0 \text{ arcsec}$ .

The other telescope used by us for monitoring the RIQs is the 201-cm Himalayan Chandra Telescope (HCT) located at Indian Astronomical Observatory (IAO), Hanle, India. It is also of the RC design with a  $f/9$  beam at the Cassegrain focus.<sup>2</sup> The detector was a cryogenically cooled  $2048 \times 4096$  chip, of which the central  $2048 \times 2048$  pixels were used. The pixel size is  $15 \mu\text{m}^2$  so that

<sup>1</sup>[http://www.iucaa.ernet.in/per cent7Eitp/igoweb/igo\\_tele\\_and\\_inst.htm](http://www.iucaa.ernet.in/per cent7Eitp/igoweb/igo_tele_and_inst.htm)

<sup>2</sup><http://www.iiap.res.in/~iao>

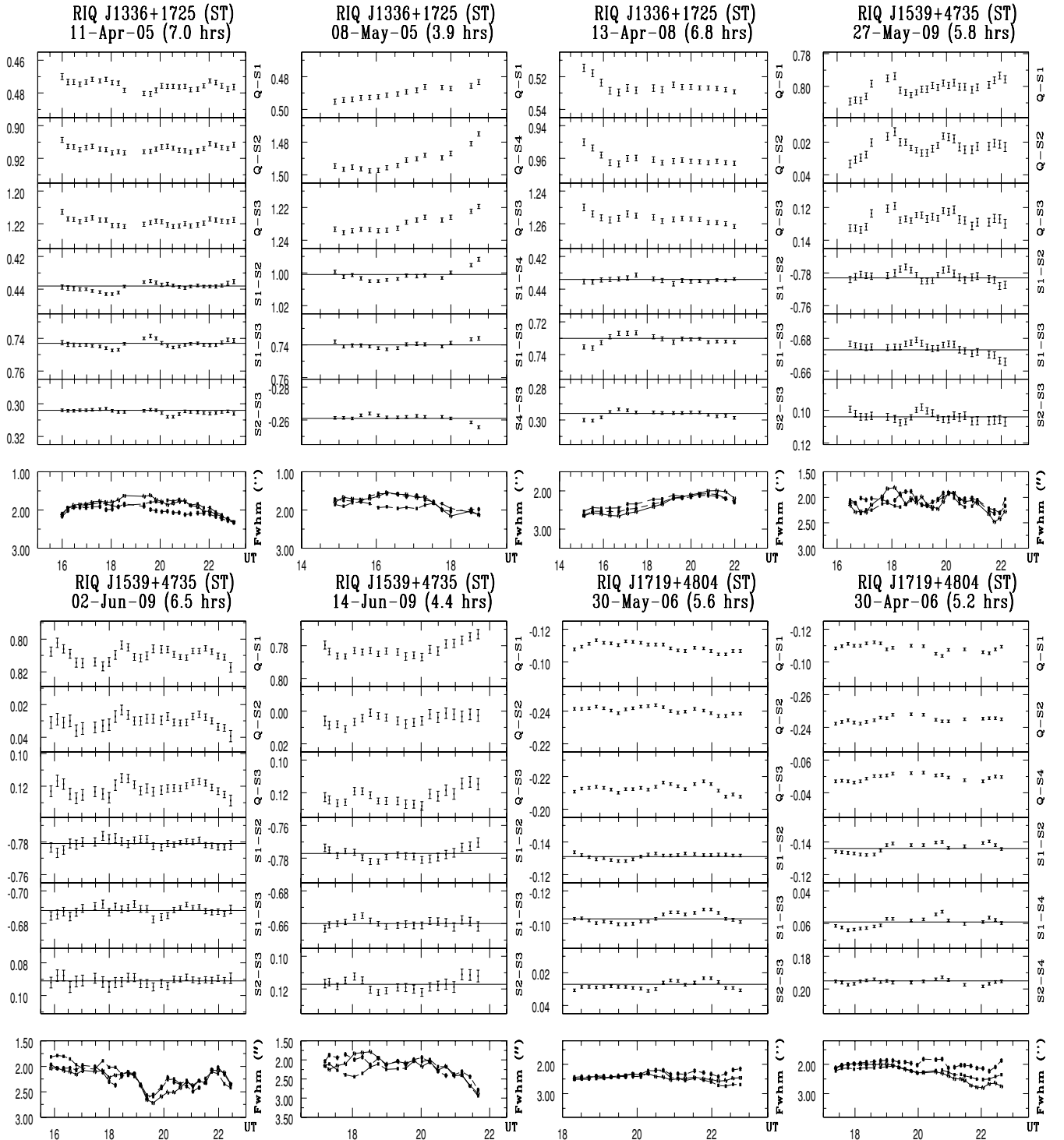


Figure 1 – continued

the image scale of  $0.29 \text{ arcsec pixel}^{-1}$  covers an area of about  $10 \times 10 \text{ arcmin}^2$  on the sky. The readout noise of CCD is  $4.87 \text{ e}^- \text{ pixel}^{-1}$  and the gain is  $1.22 \text{ e}^- \text{ ADU}^{-1}$ . The CCD was used in an unbinned mode. The seeing ranged mostly between  $\sim 1.0$  and  $\sim 4.0$  arcsec.

All the observations were made using  $R$  filter as in this band these CCDs have maximum response. The exposure time was typically 12–30 min for the ARIES and IGO observations and ranged from

3 to 6 min for observations from IAO, depending on the brightness of the source, phase of moon and the sky transparency for that night. The field positioning was adjusted so as to also have within the CCD frame 2–3 comparison stars within about a magnitude of the RIQ, in order to minimize the possibility of getting spurious variability detection (e.g. Cellone, Romero & Araudo 2007). For all three telescopes bias frames were taken intermittently and twilight sky flats were obtained.

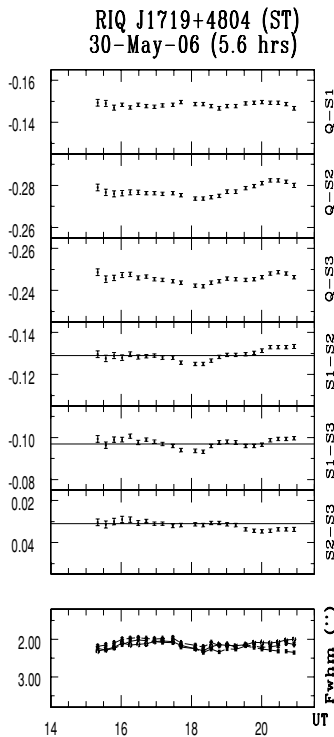


Figure 1 – continued

### 3.2 Data reduction

The pre-processing of images (bias subtraction, flat-fielding and cosmic ray removal) was done by applying the regular procedures in IRAF<sup>3</sup> and MIDAS<sup>4</sup> software. The instrumental magnitudes of the RIQ and the stars in the image frames were determined by aperture photometry, using DAOPHOT II<sup>5</sup> (Stetson 1987). The magnitude of the RIQ was measured relative to the nearly steady comparison stars present on the same CCD frame (Table 2). This way, differential light curves (DLCs) of each RIQ were derived relative to two or three comparison stars. For each night, the selection of optimum aperture radius was done on the basis of the observed dispersions in the star–star DLCs for different aperture radii starting from the median seeing [full width at half-maximum (FWHM)] value on that night up to four times that value. The aperture selected was the one which showed minimum scatter for the steadiest DLC found for the various pairs of the comparison stars (e.g. Stalin et al. 2004a).

## 4 RESULTS

### 4.1 Differential light curves

Fig. 1 shows the intranight DLCs obtained for RIQs monitored in the present study. We later combined each intranight DLC for a particular RIQ and produced its long-term optical variability (LTOV) DLC relative to the same set of steady stars that we had used for making the intranight DLCs. These LTOV DLCs are shown in Fig. 2. In Table 3, we summarize the observations for the entire sample of RIQs including the two RIQs added from the literature. For each night of observation we list the object name, date of monitoring,

**Table 2.** Positions and magnitudes of the RIQs and the comparison stars used in the present study.<sup>a</sup>

Source	RA (J2000)	Dec. (J2000)	<i>B</i> (mag)	<i>R</i> (mag)	<i>B</i> – <i>R</i>
J0748+2200	07 <sup>h</sup> 48 <sup>m</sup> 15 <sup>s</sup> .43	+22°00′59″.6	16.25	15.59	0.66
S1	07 <sup>h</sup> 48 <sup>m</sup> 03 <sup>s</sup> .57	+22°03′48″.8	16.56	16.47	0.09
S2	07 <sup>h</sup> 48 <sup>m</sup> 01 <sup>s</sup> .31	+22°00′10″.7	15.64	15.17	0.47
S3	07 <sup>h</sup> 47 <sup>m</sup> 58 <sup>s</sup> .65	+22°01′34″.9	16.31	15.83	0.48
J0832+3707	08 <sup>h</sup> 32 <sup>m</sup> 25 <sup>s</sup> .35	+37°07′36″.7	15.42	15.57	–0.15
S1	08 <sup>h</sup> 32 <sup>m</sup> 39 <sup>s</sup> .63	+37°12′17″.7	16.85	15.16	1.69
S2	08 <sup>h</sup> 32 <sup>m</sup> 39 <sup>s</sup> .78	+37°11′56″.5	17.02	15.59	1.43
S3	08 <sup>h</sup> 32 <sup>m</sup> 29 <sup>s</sup> .94	+37°11′30″.2	16.05	15.34	0.71
J0836+4426	08 <sup>h</sup> 36 <sup>m</sup> 58 <sup>s</sup> .91	+44°26′02″.4	15.46	15.44	0.02
S1	08 <sup>h</sup> 37 <sup>m</sup> 07 <sup>s</sup> .62	+44°25′57″.9	15.87	15.05	0.82
S2	08 <sup>h</sup> 37 <sup>m</sup> 14 <sup>s</sup> .23	+44°21′33″.5	17.27	15.73	1.54
S3	08 <sup>h</sup> 36 <sup>m</sup> 54 <sup>s</sup> .69	+44°22′50″.1	17.22	16.11	1.11
S4	08 <sup>h</sup> 37 <sup>m</sup> 10 <sup>s</sup> .75	+44°22′14″.7	15.60	14.29	1.31
J0907+5515	09 <sup>h</sup> 07 <sup>m</sup> 43 <sup>s</sup> .64	+55°15′12″.5	17.27	17.38	–0.11
S1	09 <sup>h</sup> 07 <sup>m</sup> 33 <sup>s</sup> .94	+55°18′10″.7	17.56	16.69	0.87
S2	09 <sup>h</sup> 07 <sup>m</sup> 33 <sup>s</sup> .98	+55°13′30″.2	17.89	16.47	1.42
S3	09 <sup>h</sup> 07 <sup>m</sup> 42 <sup>s</sup> .29	+55°11′33″.0	17.66	16.64	1.02
J1259+3423	12 <sup>h</sup> 59 <sup>m</sup> 48 <sup>s</sup> .79	+34°23′22″.8	17.31	16.06	1.25
S1	12 <sup>h</sup> 59 <sup>m</sup> 43 <sup>s</sup> .91	+34°23′22″.3	17.35	15.25	2.1
S2	13 <sup>h</sup> 00 <sup>m</sup> 18 <sup>s</sup> .24	+34°21′46″.9	18.54	15.71	2.83
S3	13 <sup>h</sup> 00 <sup>m</sup> 20 <sup>s</sup> .69	+34°23′06″.5	16.39	14.55	1.84
J1336+1725	13 <sup>h</sup> 36 <sup>m</sup> 02 <sup>s</sup> .00	+17°25′13″.1	17.11	15.84	1.27
S1	13 <sup>h</sup> 35 <sup>m</sup> 59 <sup>s</sup> .44	+17°31′20″.6	17.26	15.31	1.95
S2	13 <sup>h</sup> 36 <sup>m</sup> 21 <sup>s</sup> .27	+17°26′36″.3	16.84	14.89	1.95
S3	13 <sup>h</sup> 36 <sup>m</sup> 17 <sup>s</sup> .66	+17°28′05″.7	17.68	14.71	2.97
S4	13 <sup>h</sup> 35 <sup>m</sup> 31 <sup>s</sup> .90	+17°21′31″.6	16.00	14.42	1.58
J1539+4735	15 <sup>h</sup> 39 <sup>m</sup> 34 <sup>s</sup> .80	+47°35′31″.4	16.25	15.16	1.09
S1	15 <sup>h</sup> 39 <sup>m</sup> 11 <sup>s</sup> .40	+47°30′56″.9	16.21	14.64	1.57
S2	15 <sup>h</sup> 39 <sup>m</sup> 13 <sup>s</sup> .01	+47°30′18″.7	16.89	15.28	1.61
S3	15 <sup>h</sup> 39 <sup>m</sup> 42 <sup>s</sup> .35	+47°35′07″.1	16.74	15.42	1.32
J1719+4804	17 <sup>h</sup> 19 <sup>m</sup> 38 <sup>s</sup> .25	+48°04′12″.5	14.98	14.25	0.73
S1	17 <sup>h</sup> 19 <sup>m</sup> 14 <sup>s</sup> .96	+48°03′56″.5	17.50	16.84	0.66
S2	17 <sup>h</sup> 19 <sup>m</sup> 18 <sup>s</sup> .22	+48°08′02″.6	15.40	14.62	0.78
S3	17 <sup>h</sup> 19 <sup>m</sup> 13 <sup>s</sup> .68	+48°04′50″.5	17.50	16.67	0.83
S4	17 <sup>h</sup> 18 <sup>m</sup> 56 <sup>s</sup> .21	+48°06′44″.9	15.23	14.44	0.79

<sup>a</sup>From the United States Naval Observatory-B catalogue. Note that these magnitudes are only accurate up to 0.3 mag and the uncertainty in position is 2 arcsec (Monet et al. 2003).

telescope used, duration of the observation, number of data points ( $N_{\text{points}}$ ) in the DLC, average rms of the pairs of star–star DLC, the INOV amplitude ( $\psi$ ) and  $C_{\text{eff}}$ , an indicator of variability status and the reference for the INOV data. The classification ‘variable’ (V) or ‘non-variable’ (N) was decided using the parameter  $C_{\text{eff}}$ , basically defined following the criteria of Jang & Miller (1997). We define C for a given DLC as the ratio of its standard deviation,  $\sigma_T$ , and  $\eta\sigma_{\text{err}}$ , where  $\sigma_{\text{err}}$  is the average of the rms errors of its individual data points and  $\eta$  was estimated to be 1.5 (Gopal-Krishna et al. 2003; Sagar et al. 2004; Stalin et al. 2004a,b, 2005). However, our analysis for the present data set yields  $\eta = 1.3$  and we have adopted this value here. We compute  $C_{\text{eff}}$  from the C values (as defined above) found for the DLCs of an AGN relative to different comparison stars monitored on a given night (details are given in Sagar et al. 2004). This has the advantage of using multiple DLCs of an AGN, relative to the different comparison stars. The source is termed ‘V’ for  $C_{\text{eff}} > 2.576$ , corresponding to a confidence level of >99 per cent. We call the source a ‘probable variable’ (PV) if  $C_{\text{eff}}$  is in range of 1.950 to 2.576, corresponding to a confidence level between 95 and 99 per cent. Finally, the peak-to-peak INOV amplitude is calculated using

<sup>3</sup>IMAGE REDUCTION AND ANALYSIS FACILITY.

<sup>4</sup>MUNICH IMAGE AND DATA ANALYSIS SYSTEM.

<sup>5</sup>DOMINION ASTROPHYSICAL OBSERVATORY PHOTOMETRY.

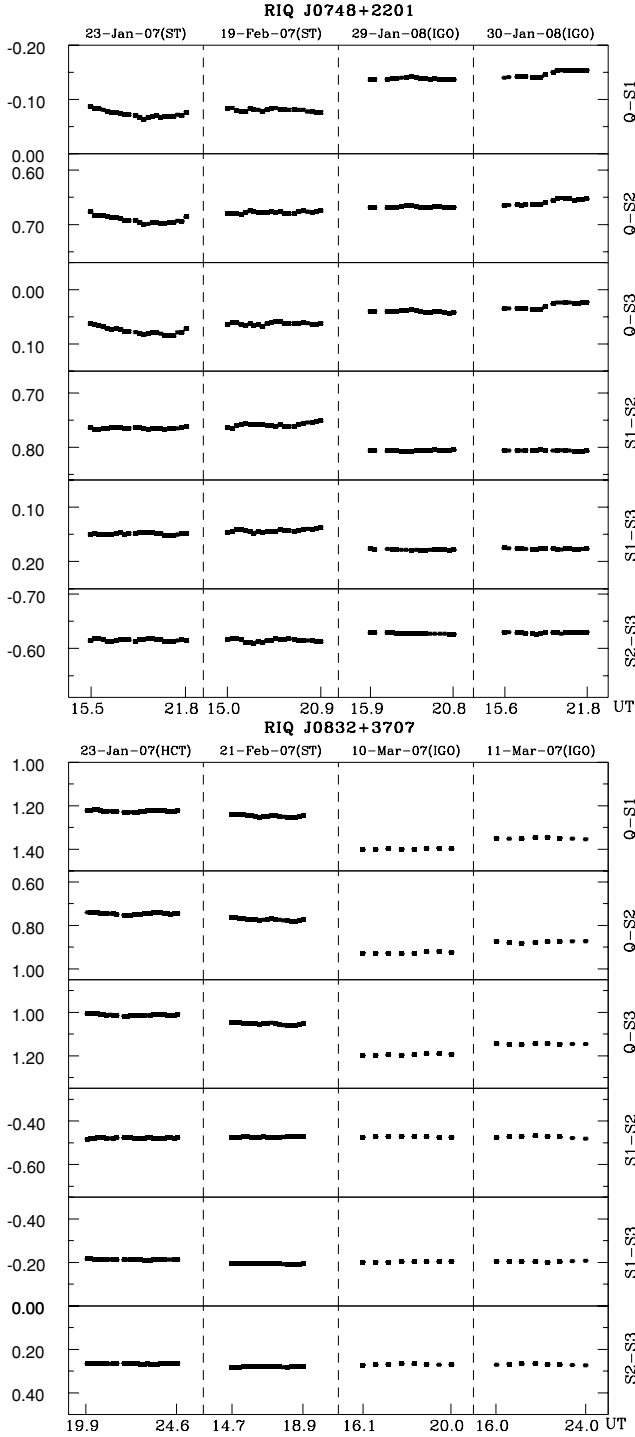


Figure 2. The LTOV DLCs of RIQs monitored in the present sample.

the definition (Romero, Cellone & Combi 1999)

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

with  $D_{\max}$  = maximum in the AGN's DLC,  $D_{\min}$  = minimum in the AGN's DLC and  $\sigma^2 = \eta^2(\sigma_{\text{err}}^2)$ .

#### 4.2 The INOV duty cycle

The INOV DC for our entire sample of RIQs (Table 3) was computed following the definition of Romero, Cellone & Combi (1999) (see

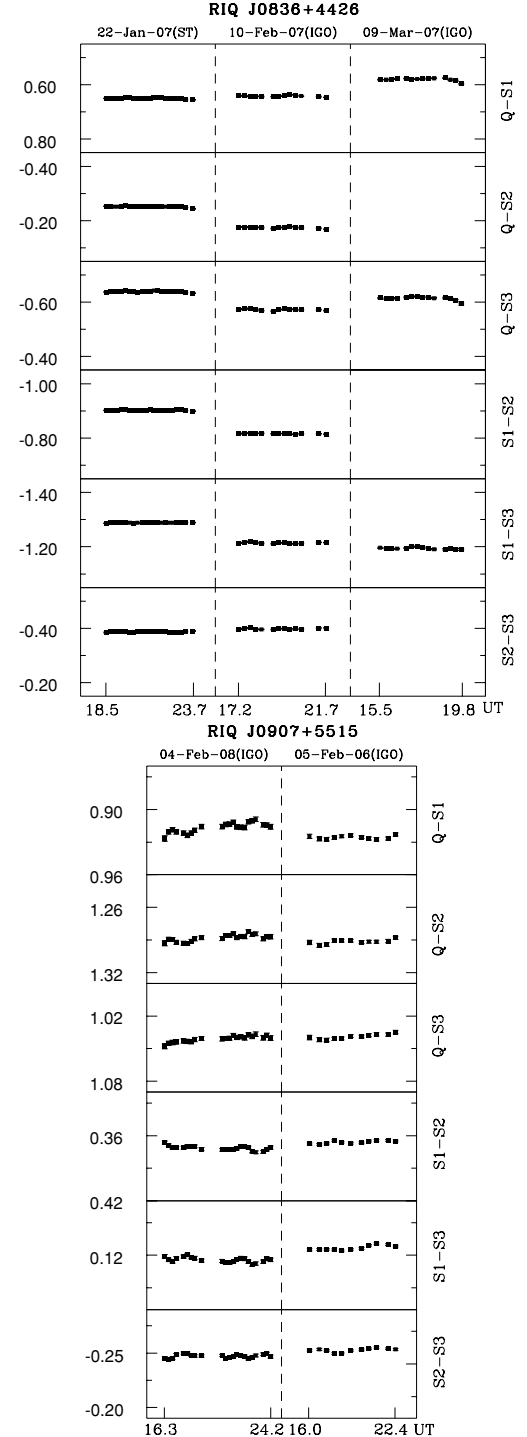


Figure 2 – continued

also Stalin et al. 2004a):

$$\text{DC} = 100 \frac{\sum_{i=1}^n N_i(1/\Delta t_i)}{\sum_{i=1}^n (1/\Delta t_i)} \text{ per cent}, \quad (2)$$

where  $\Delta t_i = \Delta t_{i,\text{obs}}(1+z)^{-1}$  is the duration of monitoring session of a RIQ on the  $i$ th night, corrected for the RIQ's cosmological redshift,  $z$ ;  $N_i$  was set equal to 1 if INOV was detected, otherwise  $N_i = 0$ . Note that since the duration of monitoring of a given source was not the same on all the nights, the computation has been weighted by the actual duration of monitoring,  $\Delta t_i$ .



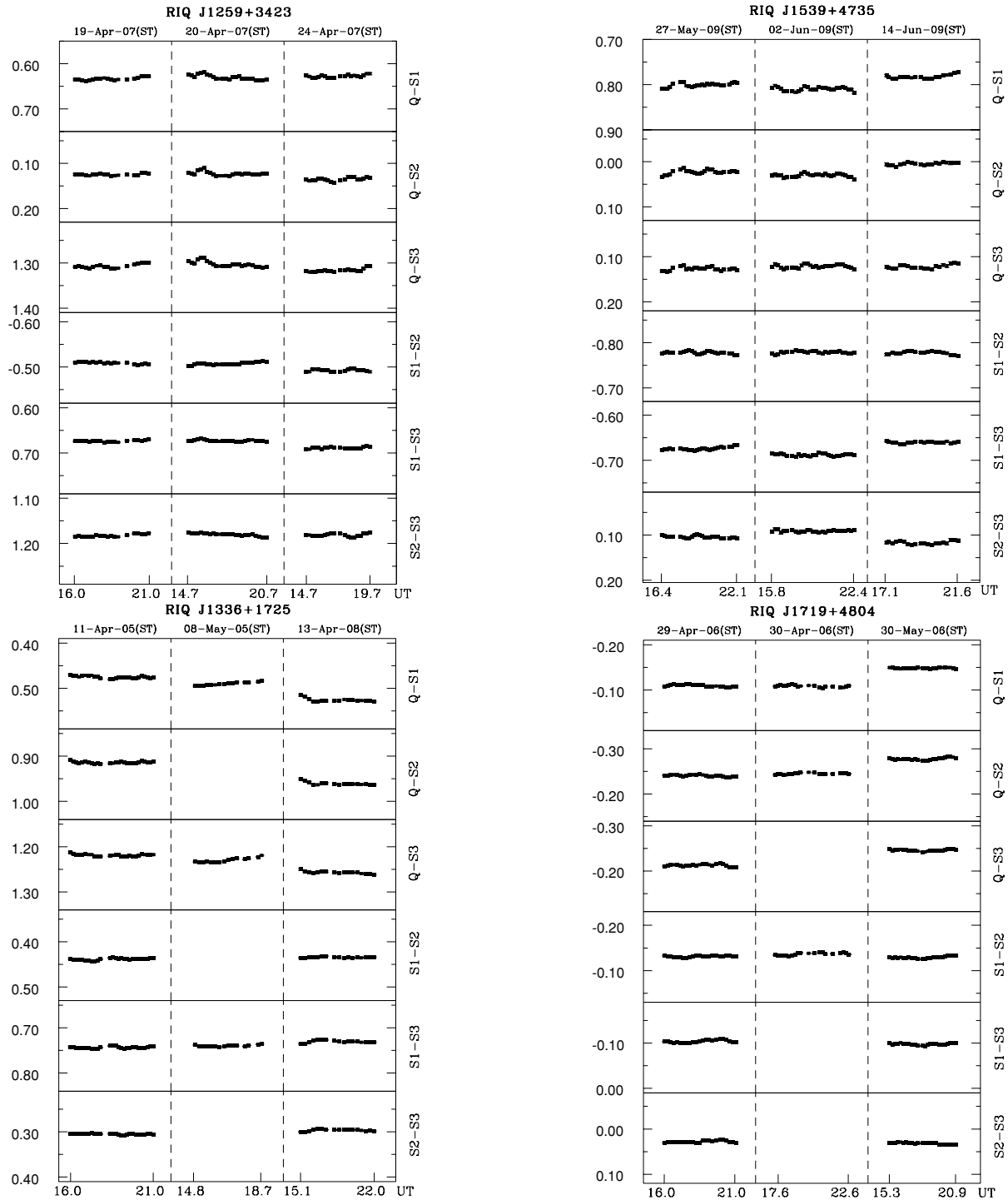


Figure 2 – continued

Figure 2 – continued

Although the data taken from the literature were in some cases in  $V$  band instead of  $R$  band, for the present purpose we do not distinguish between the  $V$  and  $R$  bands. In this manner, we computed the INOV DC for our entire data set of 42 nights. It was found to be only  $\sim 9$  per cent, which increases to  $\sim 14$  per cent if the two cases of probable INOV are also included (Table 3). Note that even for ‘P’ and ‘PV’ cases, the INOV amplitude always remained modest, with  $\psi < 3$  per cent.

As noted in Table 1, optical polarization measurements are available for six of our total 10 RIQs and in each case  $P_{\text{op}} < 1$  per

cent, while the value that nominally defines the highly polarized AGNs is  $P_{\text{op}} > 3$  per cent (e.g. Impey & Tapia 1990); therefore, at least these six RIQs lack a strong blazar-like synchrotron component in the optical band despite having flat/inverted radio spectrum (Table 1). It is worth recalling that for single epoch measurements about 90 per cent of radio selected BL Lacs show  $P_{\text{op}} > 3$  per cent, while about half of the X-ray selected BL Lacs evince that same high polarization level (Januzzi, Smith & Elston 1994). Therefore, only rarely will an intrinsically highly polarized object be observed as a lowly polarized object.

**Table 3.** Summary of observations and the INOV parameters.

Source	Date (dd.mm.yy)	Tel. used	Filter	Duration (h)	$N_{\text{points}}$	$\sigma$ (per cent)	$\psi$ (per cent)	$C_{\text{eff}}$	Status <sup>a</sup>	References
J0748+2200	23.01.07	ST	R	6.4	23	0.17	2.3	2.58	PV <sup>b</sup>	(a)
J0748+2200	19.02.07	ST	R	5.9	22	0.26	0.7	0.40	N	(a)
J0748+2200	29.01.08	IGO	R	4.9	17	0.09	0.5	0.76	N	(a)
J0748+2200	30.01.08	IGO	R	5.5	18	0.10	1.4	5.10	V§	(a)
J0832+3707	23.01.07	HCT	R	4.6	27	0.15	1.2	1.76	N	(a)
J0832+3707	21.02.07	ST	R	4.2	19	0.15	1.5	1.58	N	(a)
J0832+3707	10.03.07	IGO	R	4.0	08	0.16	0.8	0.63	N	(a)
J0832+3707	11.03.07	IGO	R	4.0	08	0.30	0.6	0.28	N	(a)
J0836+4426	22.01.07	ST	R	5.2	22	0.12	0.9	0.74	N	(a)
J0836+4426	10.02.07	IGO	R	3.9	13	0.35	1.1	1.08	N	(a)
J0836+4426	09.03.07	IGO	R	4.2	14	0.26	2.1	1.54	N	(a)
J0909+5515	04.02.08	IGO	R	4.2	22	0.20	1.2	0.68	N	(a)
J0909+5515	05.02.08	IGO	R	6.4	11	0.17	0.5	0.36	N	(a)
J1259+3423	11.05.98		V/R	5.8					N	(b)
J1259+3423	12.05.98		V/R	6.9					N	(b)
J1259+3423	19.04.07	ST	R	5.0	19	0.22	1.0	0.81	N	(a)
J1259+3423	20.04.07	ST	R	5.9	25	0.25	1.9	2.50	PV	(a)
J1259+3423	24.04.07	ST	R	3.9	20	0.25	1.1	0.59	N	(a)
J1312+3515	27.02.00		V/R	4.0					N	(b)
J1312+3515	29.02.00		V/R	6.0					N	(b)
J1312+3515	02.03.00		V/R	5.0					N	(b)
J1312+3515	08.03.99	ST	R	6.7	39				N	(c)
J1312+3515	01.04.01	ST	R	4.6	32				N	(c)
J1312+3515	02.04.01	ST	R	5.2	41				N	(c)
J1336+1725	11.04.05	ST	R	7.0	27	0.18	0.9	0.65	N	(a)
J1336+1725	08.05.05	ST	R	3.9	16	0.31	1.4	1.95	N	(a)
J1336+1725	13.04.08	ST	R	6.9	17	0.19	1.3	1.02	N	(a)
J1539+4735	21.04.01		R	5.0		1.20			N	(d)
J1539+4735	27.05.09	ST	R	5.8	26	0.31	1.6	0.99	N	(a)
J1539+4735	02.06.09	ST	R	6.5	28	0.22	1.4	0.48	N	(a)
J1539+4735	14.06.09	ST	R	4.4	20	0.26	1.2	0.53	N	(a)
J1701+5149	04.06.99		V/R	5.8					N	(b)
J1701+5149	05.06.99		V/R	4.9					N	(b)
J1701+5149	06.06.99		V/R	5.1					N	(b)
J1701+5149	07.06.99		V/R	5.7					N	(b)
J1701+5149	26.06.02		R	5.3		1.00		3.1	V	(d)
J1719+4804	01.08.94		V/R	3.3		0.90		2.6	V	(e)
J1719+4804	05.08.94		V/R	3.8		1.10			N	(e)
J1719+4804	11.06.98		R	7.6		0.90			N	(d)
J1719+4804	29.04.06	ST	R	4.5	22	0.15	0.8	1.62	N	(a)
J1719+4804	30.04.06	ST	R	5.0	26	0.13	0.6	1.20	N	(a)
J1719+4804	30.05.06	ST	R	4.6	24	0.17	0.6	0.66	N	(a)

<sup>a</sup>V = variable; N = non-variable; PV = probable variable.

<sup>b</sup>See text for explanation (Section 4.2).

References for INOV data: (a) present work; (b) Carini et al. (2007); (c) Sagar et al. (2004); (d) Jang (2005); (e) Jang & Miller (1995).

## 5 NOTES ON INDIVIDUAL SOURCES

*RIQ J0748+2200.* We monitored this RIQ on four nights spanning about a year. Formally significant variations with  $\psi \sim 2.3$  and 1.4 per cent were seen on 2007 January 23 and 2008 January 30, respectively. Note that this RIQ has a contaminating nearby faint object  $\sim 8.0$  arcsec offset along position angle (PA)  $\sim 229^\circ$ . Still we have carried out aperture photometry, following the argument (Howell 1990) that for moderately clustered objects, i.e. those separated by  $\geq 2 \times \text{FWHM}$  from the companion, the technique of optimum extraction based on aperture growth curve method can be

taken as a viable alternative to the traditional crowded point source photometry.

The mild variability noticed on 2007 January 23 might be an artefact of rather poor seeing (which varied between to 2.5 and 3.5 arcsec). Indeed the seeing variation (plotted at the bottom of the DLCs in Fig. 1) does seem partially correlated with the observed variation of the RIQ–star DLCs. Therefore, we prefer to designate this RIQ as probably variable (PV) on this night (despite  $C_{\text{eff}} = 2.58$ ). A high statistical significance was also estimated for the INOV seen on 2007 January 30, when the RIQ brightened by  $\sim 1.4$  per cent (Fig. 1). Although in this case too, the brightening

coincides with the time when the seeing changed from 2.0 to 2.5 arcsec (between UT 18.0 and 19.5 h), we do not see any general correlation between the variations of seeing and the source magnitude and there is also a very high value of  $C_{\text{eff}} = 5.1$  for this night. Taking this into account we have designated this RIQ as variable (V) on this night (Table 3). However, on the longer term, this RIQ showed no variability, with  $\psi < 0.02$  mag over the time-span of  $\sim 1$  yr (Fig. 2). Note, however, that the comparison star S1 showed a brightness dip by  $\sim 0.03$  mag over that period.

*RIQ J0832+3707.* We monitored this RIQ on four nights spanning seven weeks. No INOV was detected; however, this RIQ remains thus far our best case of internight variability, showing a fading by  $\sim 0.06$  mag between 2007 February 21 and 2007 March 10 and a brightening of  $\sim 0.02$  mag by the following night (Fig. 2).

*RIQ J0836+4426.* This RIQ did not show INOV on any of the three nights it was monitored over the time span of 45 d. In the longer term, it showed a fading by 0.05 mag, between 2007 January 22 and 2007 February 10, followed by a  $\sim 0.02$  mag brightening at the time of its last observations on 2007 March 9. Here too, the S1 varied by about 0.04 mag between the first and second dates it was observed.

*RIQ J0907+5515.* We monitored this RIQ on two consecutive nights, but found no INOV down to a limit of 0.02 mag. Furthermore, no variability was detected between the two nights.

*RIQ J1259+3423.* Out of the three nights we monitored this RIQ, it is classified as ‘probable variable’ on the night of 2007 April 20. Earlier, Carini et al. (2007) monitored it for four nights during 1998. While they did not detect significant intranight fluctuations, internight variability of  $\sim 0.2$  mag was detected by them over the course of 60 h. In our observations spanning 6 d, this RIQ showed no internight variability.

*RIQ J1336+1725.* This RIQ remained non-variable on all the three nights it was monitored by us in the course of 3 yr. In the longer term, it has shown a moderate fading by  $\sim 0.03$  mag over a year (Fig. 2).

*RIQ J1539+4735.* Based on the three nights’ monitoring over the time span of 18 d, no significant INOV or LTOV was detected (Figs 1 and 2). It had earlier been monitored by Jang (2005) for a single night but, again, no INOV was detected (Table 3).

*RIQ J1719+4804.* We monitored this RIQ on three nights over a month, but no INOV was detected. Likewise, internight change was also not found between 2006 April 29 and the following night. However, a brightening by 0.04 mag was observed between 2006 April 30 and 2006 May 30 (Fig. 2). Jang & Miller (1995) monitored this RIQ on two nights during 1994, for durations of 3.3 and 3.8 h. They report confirmed INOV on the former night (Table 3). Even though their monitoring durations fall marginally short of our criterion, we have included their data in the present study (Table 3).

For the two RIQs not covered in our monitoring programme, the summary of INOV and LTOV results, taken from the literature, is as follows.

*RIQ J1312+3515.* This RIQ was monitored by Carini et al. (2007) for three nights but no INOV was detected (Table 3). They do not comment on any longer term fluctuations over the 4-d time-span covered by their observations. Although INOV remained undetected also in the three nights’ monitoring of this RIQ by Sagar et al. (2004) (Table 3), a 0.10 mag fading was found between the first two epochs of their monitoring programme, separated by 2 yr.

*RIQ J1701+5149.* This RIQ was monitored on four nights by Carini et al. (2007), but no INOV was seen (Table 3). Furthermore, significant fluctuations were found to be absent both on internight

or longer time-scales. This RIQ was also monitored by Jang (2005) who detected a confirmed INOV ( $C_{\text{eff}} = 3.1$ , Table 3).

## 6 DISCUSSION AND CONCLUSIONS

The results reported here for a well defined, representative sample of flat/inverted spectrum RIQs provide a large increase over the existing information, both in terms of sample size and observing time. Thus, they permit the first good estimate of the INOV characteristics of RIQs and allow their comparison with those of the major AGN classes that are widely separated in the degree of radio loudness. The INOV mechanism for the major AGN classes continues to be debated (Section 1). For the (jet-dominated) blazars, INOV is believed to be associated with irregularities in the non-thermal Doppler boosted jet flow, impacted by shocks (e.g. Blandford & Königl 1979; Miller, Carini & Goodrich 1989; Marscher 1996). In contrast, the instabilities or perturbations within the accretion disc might contribute very significantly to the INOV in the case of RQQs (e.g. Wiita et al. 1991; Mangalam & Wiita 1993), particularly since any contribution from the jet must be weak.

To put the question of INOV of RIQs in perspective one may recall the known INOV characteristics of blazars (e.g. Heidt & Wagner 1996; Dai et al. 2001; Romero et al. 2002; Xie et al. 2002; Sagar et al. 2004; Stalin et al. 2005) and RQQs (e.g. Gopal-Krishna et al. 1993, 2003; Jang & Miller 1995, 1997; Stalin et al. 2005; Carini et al. 2007). The major findings of these studies are that blazars tend to vary more frequently and more strongly ( $\psi > 3$  per cent) on intranight time-scales, in stark contrast to RQQs and even to non-blazar RLQs, which show only mild INOV (i.e.  $\psi < 3$  per cent; Stalin et al. 2004b). Moreover, for monitoring durations in excess of  $\sim 4$  h, the INOV DC is  $\gtrsim 60$  per cent for BL Lacs (Carini 1990; Miller & Noble 1996; Romero et al. 2002; Gopal-Krishna et al. 2003; Stalin et al. 2005), mostly with large INOV amplitudes ( $\psi > 3$  per cent; Gopal-Krishna et al. 2003) but the DC is only  $\lesssim 15$  per cent for RQQs (Jang & Miller 1995, 1997; de Diego et al. 1998; Romero et al. 1999; Gopal-Krishna et al. 2003; Stalin et al. 2004b), or even core-dominated RLQs (Stalin et al. 2004b; Ramírez et al. 2009).

Thus, the key result from the present study is that the INOV DC for RIQs is small ( $\sim 10$  per cent), and clearly not greater than that known for RQQs and non-blazar-type RLQs. Although exact values of computed DCs will depend upon the sample and analysis technique, the key difference in INOV frequency is between blazars and both radio-loud and radio-quiet non-blazar classes (Stalin et al. 2004b, 2005) as also confirmed recently by Ramírez et al. (2009). Moreover, on no occasion (among the 42 nights) do we have the evidence for an INOV amplitude exceeding 3 per cent level, even though each of the 10 RIQs was monitored for at least  $\sim 4$  h in every session (Section 1; Table 3). Specifically, the monitoring durations in our programme ranged between 3.9 and 7.6 h, with an average of 5.2 h. As emphasized by Carini (1990), the duration of monitoring in a given session can play a substantial role in determining the INOV status of an AGN, such that the probability of confirmed INOV detection in BL Lacs is found to increase from 50 to 80 per cent if the duration of monitoring is raised from  $\sim 3$  to  $\sim 8$  h. A similar dependence on monitoring duration has been noticed for RQQs, where the chances of INOV detection increases to  $\sim 24$  per cent if the monitoring is done for  $\sim 6$ –7 h (de Diego et al. 1998; Carini et al. 2007). It is conceivable that the INOV DC of  $\sim 9$ –14 per cent estimated here for RIQs may go up marginally when longer monitoring sessions become possible, but this is unlikely to alter our main conclusions.

The simplest explanation for the difference in variability is to assume that all quasars do possess nuclear radio jets, with the differences in both observed INOV DCs and amplitudes explained by different Doppler boosting arising from both different viewing angles and different shock velocities (e.g. Gopal-Krishna et al. 2003). Another possible explanation for the low INOV DC would involve dilution of jet's optical emission by the expected accretion disc emission; however, this is unlikely to be important here, since all the RIQs in our sample lie at small redshifts ( $z < 1.5$ ; Table 1) whereas the bulk of the continuum emission of the disc would be expected to arise in the far-ultraviolet (UV) and would only move in the  $R$  band for  $z > 2$  (e.g. Bachev, Strigachev & Semkov 2005; Carini et al. 2007). Furthermore, since all but one of these RIQs have  $M_B < -24.5$ , the chance of the host galaxies' stellar continua diluting the INOV when compared to the other classes of QSOs is also very small.

Were the INOV properties of AGNs to depend primarily on the beamed radio emission, one would expect stronger and more frequent INOV for our sample of RIQs, as compared to that found for RQQs. Such an expectation would be in tune with the widely held notion that RIQs are Doppler boosted counterparts of RQQs, as inferred from their high brightness temperature ( $T_B$ ), prominent radio cores and low extended fluxes at radio wavelengths, measured using milli-arcsecond resolution radio images available for a few RIQs (Section 1). The INOV data reported here do not accord well these broad expectations, since we have found the INOV of RIQs to be as mild as that known for RQQs.

Thus, the RIQ PG 0007+106 (III Zw 2) remains the only well established case for which a blazar-like, large and rapid flux variability has been detected (both at radio and optical wavelengths, Section 1). In particular, the source was found by Jang & Miller (1997) to vary by up to 0.1 mag on each the two nights they monitored it for 4-h duration. Interestingly, the observed high level of activity would not have been anticipated, given that this object was found to show a very low optical polarization:  $P_{op} = 0.28 \pm 0.19$  per cent (Berriman et al. 1990). The RIQ III Zw 2 underwent a slow fading by  $\sim 0.8$  mag between 1978 and 1981, after which it displayed rapid flares of increasing amplitude, brightening by 0.92 mag in 27 d during 1985 November and then fading by 0.95 mag in the following week (Pica et al. 1988). Such large variability, along with the observed INOV (see above), is clearly characteristic of optical violently variable (OVV) type blazars. In the longer term, its optical light curve has shown a fourfold variation in 25 yr (Salvi et al. 2002) and, likewise, a 20-fold brightening within 4 yr has been recorded at radio wavelengths (Aller et al. 1985). All these variability properties firmly place this object in the blazar category (Kukula et al. 1998; Aller et al. 1999; Teräsranta et al. 2005). In contrast, none of the 10 RIQs in our representative sample qualify for the blazar classification, on the basis of the currently available data summarized above.

The present observations are also useful for measuring any LTOV occurring on month-like or longer time-scales. For the vast majority of RIQs, which are represented by the present sample and which are hosted by luminous (very likely elliptical) galaxies, we find the optical variability to be very common on month/year-like time-scales, with typical amplitude approaching 0.1-mag level in  $R$  band. This RIQ specific result is in accord with the findings reported by Webb & Malkan (2000) for more common AGN types. For roughly half the AGNs they found optical variability amplitudes of 0.1–0.2 mag (rms) on month-like time-scale. A similar pattern is reported by Barvainis et al. (2005), based on their 10-epoch VLA radio variability survey of a large sample consisting of RQQs, RIQs and RLQs. They found no statistical difference between the degrees of radio variability displayed by these three major subclasses of

quasars. Thus, both intranight and LTOV properties, together with the other aforementioned evidence from the literature, demonstrate that as a class RIQs display much lower activity levels than do blazars, which would be rather surprising if they are a strongly relativistically beamed subset of RQQs, a possibility widely discussed in the literature.

The possibility that these RIQ sources possess intrinsically moderate radio jets and are not strongly Doppler boosted (in either radio or optical band) therefore must be considered. In that case either roughly comparable amounts of jet fluctuations, or even disc-dominated variability, could explain the similar INOV and LTOV properties of RIQs and RQQs. The low optical polarizations seen for RIQs in our sample (Table 1) also seem consistent with a lack of strong relativistic beaming, though the case of III Zw 2 discussed above calls for caution in reaching this inference. A key observational difference between these RIQs and the RQQs is the predominance of flat or inverted radio spectra for the former group, which is generally not the case for RQQs (e.g. Kukula et al. 1998) and which was argued to imply (at least somewhat) boosted jets in the RIQs.

One conceivable explanation then for the relative lack of INOV in RIQs would be that, because of bending of their jets on the innermost scales, their optically emitting inner portions are misdirected and hence concealed from us (despite the beaming) and only the more extended radio emitting outer parts of the jets happen to be pointed towards us. Verifying this alternative would require sensitive VLBI observations. However, an implication of this scenario is that one would expect to find some cases of blazar-like optical variability in radio-quiet AGN whose radio emitting (but not optical emitting) sections of the jet are misaligned from us. The few searches made so far for radio-quiet BL Lacs have either been negative (e.g. Stocke et al. 1990; Londish et al. 2007) or have produced a only a small fraction of candidate BL Lacs that have low, but not extremely low, upper limits to their radio fluxes (Collinge et al. 2005). Finally, it may be noted that despite the vast increase in the intranight monitoring data, as reported here, the total number of nights used for their monitoring is still modest (42 nights) when compared with those devoted to blazars and even RQQs. Since a few convincing cases of RIQs showing modest intranight or internight variability have none the less been found, it would be worthwhile to continue such observations in the search for examples of blazar-like strong INOV activity among RIQs, similar to that detected so far only for the nearest known RIQ, III Zw 2.

## ACKNOWLEDGMENTS

AG would like to thank Dr Vijay Mohan for help during observations at IGO and for a preliminary discussion on data analysis. The authors wish to acknowledge the support rendered by the staff of IAO and CREST at IIA and the IUCAA-Girawali Observatory (IGO), IUCAA. This research has made use of NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with National Aeronautics and Space Administration.

## REFERENCES

- Aller H. D., Aller M. F., Latimer G. E., Hodge P. E., 1985, *ApJS*, 59, 513
- Aller M. F., Aller H. D., Hughes P. E., Philip A., Latimer G. E., 1999, *ApJ*, 512, 601
- Arp H., 1968, *ApJ*, 152, 1101
- Bachev R., Strigachev A., Semkov E., 2005, *MNRAS*, 358, 774
- Barvainis R., Joseph L., Birkinshaw M., Falcke H., Blundell K. M., 2005, *ApJ*, 618, 108

- Becker R. H., White R. L., Helfand D. J., 1995, *ApJ*, 450, 559
- Berriman G., Schmidt G. D., West S. C., Stockman H. S., 1990, *ApJS*, 74, 869
- Blandford R. D., 1990, in Blandford R. D., Netzer H., Woltjer L., eds, *Active Galactic Nuclei, Saas-Fee Advanced Course 20*. Springer-Verlag, Berlin, p. 161
- Blandford R. D., Königl A., 1979, *ApJ*, 232, 34
- Blundell K. M., Beasley A. J., 1998, *MNRAS*, 299, 165
- Blundell K. M., Rawlings S., 2001, *ApJ*, 562, L5
- Blundell K. M., Beasley A. J., Bicknell G. V., 2003, *ApJ*, 591, L103
- Boroson T. A., 2002, *ApJ*, 565, 78
- Brunthaler A. et al., 2000, *A&A*, 357, L45
- Brunthaler A., Falcke H., Bower G. C., Aller M. F., Aller H. D., Teräsranta H., 2005, *A&A*, 435, 497
- Carini M. T., 1990, PhD thesis, Georgia State University
- Carini M. T., Noble J. C., Miller H. R., 2003, *AJ*, 125, 1811
- Carini M. T., Noble J. C., Taylor R., Culler R., 2007, *AJ*, 133, 303
- Cellone S. A., Romero G. E., Combi J. A., 2000, *AJ*, 119, 1534
- Cellone S. A., Romero G. E., Araudo A. T., 2007, *MNRAS*, 374, 357
- Cirasuolo M., Celotti A., Magliocchetti M., Danese L., 2003, *MNRAS*, 346, 447
- Collinge M. et al., 2005, *AJ*, 129, 2542
- Condon J. J., Cotton W. D., Greisen E. W., Yin Q. F., Perley R. A., Taylor G. B., Broderick J. J., 1998, *AJ*, 115, 1693
- Corbel S. et al., 2001, *ApJ*, 554, 43
- Czerny B., Siemiginowska A., Janiuk A., Gupta A. C., 2008, *MNRAS*, 386, 1157
- Dai B. Z., Xie G. Z., Li K. H., Zhou S. B., Liu W. W., Jiang Z. J., 2001, *AJ*, 122, 2901
- de Diego J. A., Dultzin-Hacyan D., Ramírez A., Benitez E., 1998, *ApJ*, 501, 69
- Diamond-Stanic A. M. et al., 2009, *ApJ*, 699, 782
- Falcke H., Malkan M. A., Biermann P. L., 1995a, *A&A*, 298, 375
- Falcke H., Gopal-Krishna, Biermann P. L., 1995b, *A&A*, 298, 395
- Falcke H., Sherwood W., Patnaik A. R., 1996a, *ApJ*, 471, 106
- Falcke H., Patnaik A. R., Sherwood W., 1996b, *ApJ*, 473, L13
- Falcke H., Lehár J., Barvainis R., Nagar N. M., Wilson A. S., 2001, in Peterson B. M., Pogge R. W., Polidan R. S., eds, *ASP Conf. Ser. Vol. 224, Probing the Physics of Active Galactic Nuclei*. Astron. Soc. Pac., San Francisco, p. 265
- Ghisellini G., Haardt F., Matt G., 2004, *A&A*, 413, 535
- Gopal-Krishna, Sagar R., Wiita P. J., 1993, *MNRAS*, 262, 969
- Gopal-Krishna, Gupta A. C., Sagar R., Wiita P. J., Chaubey U. S., Stalin C. S., 2000, *MNRAS*, 314, 815
- Gopal-Krishna, Stalin C. S., Sagar R., Wiita P. J., 2003, *ApJ*, 586, L25
- Gopal-Krishna, Mangalam A., Wiita P. J., 2008, *ApJ*, 680, L13
- Gupta A. C., Joshi U. C., 2005, *A&A*, 440, 855
- Heidt J., Wagner S. J., 1996, *A&A*, 305, 42
- Helmboldt J. F. et al., 2007, *ApJ*, 658, 203
- Hogg D., 1999, preprint (astro-ph/9905116)
- Howell S. B., 1990, in Jacoby G. H., ed., *ASP Conf. Ser. Vol. 8, CCDs in Astronomy*. Astron. Soc. Pac., San Francisco, p. 312
- Hutchings J. B., Campbell B., 1983, *Nat*, 303, 584
- Hutchings J. B., Neff S. G., Gower A. C., 1992, *PASP*, 104, 62
- Impey C. D., Tapia S., 1990, *ApJ*, 354, 124
- Ivezić Ž., Menou K., Knapp G. R., Strauss M. A., Lupton R. H., Vanden Berk D. E., Richards G. T., Tremonti C., 2002, *AJ*, 124, 2364
- Ivezić Ž. et al., 2004, in Richards G. T., Hall P. B., eds, *ASP Conf. Ser. Vol. 311, AGN Physics with the Sloan Digital Sky Survey*. Astron. Soc. Pac., San Francisco, p. 347
- Jang M., 2005, *Ap&SS*, 295, 397
- Jang M., Miller H. R., 1995, *ApJ*, 452, 582
- Jang M., Miller H. R., 1997, *AJ*, 114, 565
- Jannuzi B. T., Smith P. S., Elston R., 1994, *ApJ*, 428, 130
- Jiang L., Fan X., Ivezić Ž., Richards G. T., Schneider D. P., Strauss M. A., Kelly B. C., 2007, *ApJ*, 656, 680
- Kellermann K. I., Sramek R., Schmidt M., Shaffer D. B., Green R. F., 1989, *AJ*, 98, 1195
- Kellermann K. I., Sramek R. A., Schmidt M., Green R. F., Shaffer D. B., 1994, *AJ*, 108, 1163
- Komatsu E. et al., 2009, *ApJS*, 180, 330
- Körding E. G., Jester S., Fender R., 2006, *MNRAS*, 372, 1336
- Kukula M. L., Dunlop J. S., Hughes D. H., Rawlings S., 1998, *MNRAS*, 297, 366
- Leipski C., Falcke H., Bennert H., Hüttemeister S., 2006, *A&A*, 455, 161
- Londish D. et al., 2007, *MNRAS*, 374, 556
- Maccarone T. J., Gallo E., Fender R., 2003, *MNRAS*, 345, L19
- Mangalam A. V., Wiita P. J., 1993, *ApJ*, 406, 420
- Marscher A. P., 1996, in Miller H. R., Webb J. R., Noble J. C., eds, *ASP Conf. Ser. Vol. 110, Blazar Continuum Variability*. Astron. Soc. Pac., San Francisco, p. 248
- Martínez A., Rawlings S., Garn T., Green D. A., Alexander P., Klöckner H. R., Riely J. M., 2006, *MNRAS*, 373, L80
- Miller H. R., Noble J. C., 1996, in Miller H. R., Webb J. R., Noble J. C., eds, *ASP Conf. Ser. Vol. 110, Blazar Continuum Variability*. Astron. Soc. Pac., San Francisco, p. 17
- Miller H. R., Carini M., Goodrich B., 1989, *Nat*, 337, 627
- Miller P., Rawlings S., Saunders R., 1993, *MNRAS*, 263, 425
- Monet D. G. et al., 2003, *AJ*, 125, 984
- Osterbrock D. E., 1977, *ApJ*, 215, 933
- Pica A. J., Smith A. G., Webb J. R., Leacock R. J., Clements S., Gombala P. P., 1988, *AJ*, 96, 1215
- Rafter S. E., Crenshaw D. M., Wiita P. J., 2009, *AJ*, 137, 42
- Ramírez A., de Diego J. A., Dultzin D., Gonzalez-Perez J.-N., 2009, *AJ*, 138, 991
- 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, *Curr. Sci.*, 77, 643
- Sagar R., Stalin C. S., Gopal-Krishna, Wiita P. J., 2004, *MNRAS*, 348, 176
- Salvi N. J., Page M. J., Stevens J. A., Wu K., Mason K. O., Aller M. F., Aller H. D., Teräsranta H., 2002, *MNRAS*, 335, 177
- Sandage A., 1965, *ApJ*, 141, 1560
- Stalin C. S., Gopal-Krishna, Sagar R., Wiita P. J., 2004a, *JA&A*, 25, 1
- Stalin C. S., Gopal-Krishna, Sagar R., Wiita P. J., 2004b, *MNRAS*, 350, 175
- Stalin C. S., Gupta A. C., Gopal-Krishna, Wiita P. J., Sagar R., 2005, *MNRAS*, 356, 607
- Stetson P. B., 1987, *PASP*, 99, 191
- Stoeke J. T., Morris S. L., Gioia I., Maccacaro T., Schild R. E., Wolter A., 1990, *ApJ*, 348, 141
- Stoeke J. T., Morris S. L., Weymann R. J., Foltz C. B., 1992, *ApJ*, 396, 487
- Stockmann H. S., Moore R. L., Angel J. R. P., 1984, *ApJ*, 279, 485
- Strittmatter P. A., Hill P., Pauliny-Toth I. I. K., Steppe H., Witzel A., 1980, *A&A*, 88, L12
- Taylor G. L., Dunlop J. S., Hughes D. H., Robson E. I., 1996, *MNRAS*, 283, 930
- Teräsranta H., Tornikoski M., Mujunen A., Karlamaa K., Valtonen T., Henelius N., Urpo S., Lainela M., 1998, *A&AS*, 132, 305
- Teräsranta H., Wiren S., Koivisto P., Saarinen V., Hovatta T., 2005, *A&A*, 440, 409
- Ulvestad J. S., Antonucci R. R. J., Barvainis R., 2005, *ApJ*, 621, 123
- Véron-Cetty M.-P., Véron P., 2006, *A&A*, 455, 773
- Wang T.-G., Zhou H., Wang J.-X., Lu Y.-J., Lu Y., 2006, *ApJ*, 645, 856
- Webb W., Malkan M., 2000, *ApJ*, 540, 652
- White R. L., Becker R. H., Gregg M. D., Laurent-Muehleisen S. A., Brotherton M. S., Impey C. D., Petry C. E., Foltz C. B., 2000, *ApJS*, 126, 133
- Wiita P. J., Miller H. R., Carini M. T., Rosen A., 1991, in Bertout C., Collin-Souffrin S., Lasota J. P., eds, *Structure and Emission Properties of Accretion Disks*. Editions Frontieres, Gif-sur-Yvette, p. 557
- Wilson A. S., Colbert E. J. M., 1995, *ApJ*, 438, 62
- Xie G. Z., Liang E. W., Xie Z. H., Dai B. Z., 2002, *AJ*, 123, 2352
- Xu C., Livio M., Baum S., 1999, *AJ*, 118, 1169

This paper has been typeset from a  $\text{\TeX}/\text{\LaTeX}$  file prepared by the author.