Intranight optical variability of radio-quiet weak emission line quasars – III

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ABSTRACT
This is continuation of our programme to search for the elusive radio-quiet BL Lacs, by carrying out a systematic search for intranight optical variability (INOV) in a subset of ‘weak emission line quasars’ which are already designated as ‘high-confidence BL Lac candidate’ and are also known to be radio quiet. For six such radio-quiet weak emission line quasars (RQWLQs), we present here new INOV observations taken in 11 sessions of duration >3 h each. Combining these data with our previously published INOV monitoring of RQWLQs in 19 sessions yields INOV observations for a set of 15 RQWLQs monitored in 30 sessions, each lasting more than 3 h. The 30 differential light curves, thus obtained for the 15 RQWLQs, were subjected to a statistical analysis using the F-test, and the deduced INOV characteristics of the RQWLQs then compared with those published recently for several prominent active galactic nucleus (AGN) classes, also applying the F-test. From our existing INOV observations, there is a hint that RQWLQs in our sample show a significantly higher INOV duty cycle than radio-quiet quasars and radio lobe-dominated quasars. Two sessions when we have detected strong (blazar-like) INOV for RQWLQs are pointed out, and these two RQWLQs are therefore the best known candidates for radio-quiet BL Lacs, deserving to be pursued. For a proper comparison with the INOV properties already established for (brighter) members of several prominent classes of AGN, a factor of 2–3 improvement in the INOV detection threshold for the RQWLQs is needed and it would be very interesting to check if that would yield a significantly higher estimate for INOV duty cycle than is found here.

Key words: galaxies: active – BL Lacertae objects: general – galaxies: jet – galaxies: photometry – quasars: emission lines – quasars: general.

1 INTRODUCTION
Flux variations at all energy bands is a well-known characteristic of active galactic nuclei (AGN) (e.g. see Urry & Padovani 1995). Optical flux variation on hour-like time-scale, which is commonly known as ‘intranight optical variability’ (INOV), has emerged as a useful probe of AGN (Wagner & Witzel 1995; Ulrich, Maraschi & Urry 1997; Wiita 2006). The past two decades have witnessed a large number of INOV studies covering different classes of AGN, in order to study the physical processes underlying this phenomenon occurring in the different AGN classes (Miller, Carini & Goodrich 1989; Carini, Miller & Goodrich 1990; Carini et al. 1991, 1992, 2007; Carini & Miller 1992; Gopal-Krishna, Wiita & Altieri 1993; Gopal-Krishna, Sagar & Wiita 1995; Heidt & Wagner 1996; Stalin et al. 2004a; Gupta & Joshi 2005; Joshi et al. 2011; Goyal et al. 2013; Joshi & Chand 2013; Chand, Kumar & Gopal-Krishna 2014; de Diego 2014). These studies have led to theoretical models for INOV (e.g. see Ulrich et al. 1997; Wiita 2006; Czerny et al. 2008). For instance, in blazars, where pronounced INOV is observed, the cause could be turbulence or localized particle acceleration events within the non-thermal plasma flowing in a relativistic jet (e.g. Singal & Gopal-Krishna 1985; Wagner & Witzel 1995; Gopal-Krishna et al. 2003). On the other hand, in the case of radio-quiet quasars (RQQs) flares occurring in the accretion disc might also play a significant if not dominant role in causing the INOV (Mangalam & Wiita 1993). In gamma-ray-loud narrow-line Seyfert1 galaxies, the detection of INOV on hour-like or shorter time-scale points to the presence of non-thermal jets with large Doppler factors (Paliya et al. 2013). Hence, INOV studies of different classes of AGN can play a useful role in improving the understanding of the AGN physics.

Weak emission line quasars (WLQs) is a relatively recently discovered and rather enigmatic class of AGN (e.g. Smith et al. 2007; Plotkin et al. 2010; Heidt & Nilsson 2011). They exhibit...
abnormally weak broad emission-lines (i.e. rest-frame EW < 15.4 Å for the Ly+NV emission-line complex; Diamond-Stanic et al. 2009). The physical cause for the abnormally weak line emission continues to be debated, as summarized in the previous papers of this series (Gopal-Krishna, Joshi & Chand 2013; Chand, Kumar & Gopal-Krishna 2014, hereinafter Paper I and Paper II). It may be recalled that according to the currently prevailing view, the two sub-categories of the most active AGN, called blazars, are BL Lac objects (BLOs) and highly polarized quasars (HPQS) which differ primarily in the prominence of emission lines in the optical spectrum. But, whereas HPQS have an abundant population of (usually weakly polarized) radio-quiet counterparts (the RQQs), searches for radio-quiet analogues of BLOs have so far remained unsuccessful, even proving the radio-quiet subset of WLQs (RQWLQs) as possible candidates (e.g. Jannuzi, Green & French 1993; Londish et al. 2004).

The explanations proposed for the WLQs basically fall in two categories. One possible cause of the abnormality is the high mass of the central BH ($M_{\text{BH}} > 3 \times 10^9 M_{\odot}$) which can result in an accretion disc too cold to emit strongly the ionizing UV photons, even when its optical output is high (Laor & Davis 2011; also, Plotkin et al. 2010). Alternatively, the covering factor of the broad-line region (BLR) in WLQs could be at least an order-of-magnitude smaller compared to the normal QSOs (e.g. Nikolajuk & Walter 2012). An extreme version of this scenario is that in WLQs the accretion disc is relatively recently established and hence a significant BLR is yet to develop (Hryniewicz et al. 2010; Liu & Zhang 2011). Conceivably, a poor BLR could also result from the weakness of the radiation pressure driven wind when the AGN is operating at an exceptionally low accretion rate ($<10^{-2} - 10^{-3} M_{\text{Edd}}$; Nicastro, Martocchia & Matt 2003; also, Elitzur & Ho 2009).

While the above mechanisms may well operate commonly, a small fraction of radio-quiet weak emission line quasars (RQWLQs) may nonetheless turn out to be the radio-quiet counterparts of BL Lacs, such that the relativistic jet itself is radio quiet. In order to pursue this interesting question, we started in 2012 an observational programme aimed at determining the INOV characteristics of RQWLQs (Papers I and II). In this work (Paper III), we report the INOV results for six of the RQWLQs which we monitored for 11 nights. This paper is organized as follows. Section 2 describes our RQWLQ sample. Observations and data reduction procedures are described in Section 3. Details of our statistical analysis are presented in Section 4, followed by a brief discussion of the results in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

2.1 The sample of RQWLQs

Our sample for INOV monitoring (Table 1) was derived from the list of 86 RQWLQs published in table 6 of Plotkin et al. (2010), based on the SDSS Data Release 7 (DR-7; Abazajian et al. 2009). Of that list, we included in our sample all 19 objects which are brighter than $R \sim 18.5$ and are classified therein as ‘high-confidence BL Lac candidate’, is uncertain (the choice of rms threshold is consistent with Londish et al. 2004). Alternatively, the covering factor of the broad-line region (BLR) in WLQs could be at least an order-of-magnitude smaller compared to the normal QSOs (e.g. Nikolajuk & Walter 2012). An extreme version of this scenario is that in WLQs the accretion disc is relatively recently established and hence a significant BLR is yet to develop (Hryniewicz et al. 2010; Liu & Zhang 2011). Conceivably, a poor BLR could also result from the weakness of the radiation pressure driven wind when the AGN is operating at a relatively low accretion rate ($<10^{-2} - 10^{-3} M_{\text{Edd}}$; Nicastro, Martocchia & Matt 2003; also, Elitzur & Ho 2009). While the above mechanisms may well operate commonly, a small fraction of radio-quiet weak emission line quasars (RQWLQs) may nonetheless turn out to be the radio-quiet counterparts of BL Lacs, such that the relativistic jet itself is radio quiet. In order to pursue this interesting question, we started in 2012 an observational programme aimed at determining the INOV characteristics of RQWLQs (Papers I and II). In this work (Paper III), we report the INOV results for six of the RQWLQs which we monitored for 11 nights. This paper is organized as follows. Section 2 describes our RQWLQ sample. Observations and data reduction procedures are described in Section 3. Details of our statistical analysis are presented in Section 4, followed by a brief discussion of the results in Section 5.

| IAU Name | RA (J2000) (h m s) | Dec. (J2000) (° ′ ″) | R (mag) | z | PM (mas yr⁻¹) |
|----------|------------------|------------------|--------|--|-------------|
| J081250.79+522531.05 | 08 12 50.80 | +52 25 31 | 18.30 | 1.152 | 00 |
| J084424.20+124546.00 | 08 44 24.20 | +12 45 46 | 18.28 | 2.466 | 00 |
| J091007.60+384659.00 | 09 01 07.60 | +38 46 59 | 18.21 | 1.329 | 62.3 ± 10.8 |
| J092843.25+252259.80 | 09 28 43.25 | +25 22 59 | 18.55 | 0.930 | 00 |
| J101353.45+492757.99 | 10 13 53.45 | +49 27 57 | 18.40 | 1.635 | 00 |
| J110938.50+373611.60 | 11 09 38.50 | +37 36 11 | 18.72 | 0.397 | 10.8 ± 4.5 |
| J111401.31+222211.50 | 11 14 01.31 | +22 22 11 | 18.77 | 2.121 | 10.2 ± 2.0 |
| J115637.02+184856.50 | 11 56 37.02 | +18 48 56 | 18.42 | 1.956 | 00 |
| J112929.50+471522.00 | 11 29 29.50 | +47 15 22 | 17.66 | 1.336 | 112.1 ± 3.6 |
| J122519.50+264053.00 | 12 25 19.50 | +26 40 53 | 17.94 | 1.292 | 00 |
| J134601.29+538520.10 | 13 46 01.29 | +53 85 20 | 17.73 | 1.22 | 00 |
| J140710.26+241853.60 | 14 07 10.26 | +24 18 53 | 18.49 | 1.662 | 12.0 ± 5.1 |
| J141200.04+634414.90 | 14 12 00.04 | +63 44 14 | 17.97 | 0.068 | 00 |
| J124934.60+385932.00 | 12 49 34.60 | +38 59 32 | 17.56 | 0.925 | 00 |
| J153044.10+230141.00 | 15 30 44.10 | +23 01 41 | 17.32 | 1.040 | 00 |
| J160410.22+432614.70 | 16 04 10.22 | +43 26 14 | 18.04 | 1.568 | 00 |
| J161245.68+511817.31 | 16 12 45.68 | +51 18 17 | 17.70 | 1.595 | 2.0 ± 2.0 |
| J214216.05+071429.90 | 21 42 16.05 | +07 14 29 | 18.29 | 1.402 | 00 |
| J224749.56+134250.00 | 22 47 49.56 | +13 42 50 | 18.53 | 1.179 | 14.1 ± 3.6 |

Notes. *Result for the sources marked by * are reported in this paper. Although all these sources are classified as ‘high-confidence BL Lac candidate’ in Plotkin et al. (2010), the four sources marked by † are probably galactic, due to their significant proper motion.
et al. 2004). This is further corroborated by the fact that, based on a multiwavelength SED analysis, Wu et al. (2012) have confirmed extragalactic nature for the WLQ J110938+373611 for which USNO proper motion is 10.8 ± 4.5 mas yr−1. Likewise, for J140710+241853 and J161245+511817, non-zero redshifts have been confirmed by Hewett & Wild (2010). Therefore, we have retained these three sources in our RQWLQ sample, and removed the remaining four sources for which proper motion is detected above 2.5σ (these sources are marked with (†) in Table 1). Thus, the proper motion check reduces our sample from 19 to 15 RQWLQs and these can be regarded as bona fide ‘high-confidence BL Lac candidates’. New observations of 6 out of these 15 RQWLQs (marked by asterisk (∗) in Table 1) are reported in this work, based on 11 monitoring sessions. Note that one of the four excluded sources is J121929+471522 for which INOV detection with an amplitude of ~7 per cent over a few hours was reported in Paper I.

3 OBSERVATIONS AND DATA REDUCTION

3.1 Photometric monitoring observations

The programme to determine the INOV properties of RQWLQs, initially reported in Paper I, has been primarily carried out using the 1.3-m Devasthal Fast Optical Telescope (DFOT) of the Aryabhatta Research Institute of Observational Sciences (ARIES) located at Devasthal, India (Sagar et al. 2011). We have also used the 1.04-m Sampurnanand and IUCAA Girawali Observatory (IGO) telescopes for optical monitoring of a few of these sources (Paper I). The entire monitoring was done in the r band and each time a given RQWLQ was monitored continuously for not less than 3.5 h, except in case of J140710.26+241853.6 when the duration was a bit shorter (3.0 h, Table 4). DFOT is a fast beam (f/4) optical telescope with a pointing accuracy better than 10 arcsec rms. It is equipped with a 2k × 2k Peltier-cooled Andor CCD camera having a pixel size of 13.5 μm and a plate scale of 0.54 arcsec pixel−1. The CCD covers a field of view of 18 arcmin on the sky and is read out with 31 and 1000 kHz speeds, with the corresponding system rms noise of 2.5, 7 e− and a gain of 0.7, 2 e−/ Analog to Digital Unit (ADU), respectively. The CCD used in our observations was cooled thermoelectrically to −85°C. The duration of each science frame was about 5–7 min, yielding a typical SNR above 25–30. The FWHM (full width at half-maximum) of the seeing disc during our observing was generally ~2.5 arcsec.

In our sample selection process, care was taken to identify at least two, but usually more, comparison stars on the CCD frame that were within about 1 mag of the target RQWLQ. This allowed us to pin down and discount any comparison stars which showed variability during our observations, thus permitting a reliable differential photometry of the RQWLQ monitored.

3.2 Data reduction

The pre-processing work on the raw images (bias subtraction, flat-fielding, cosmic ray removal and trimming) was carried out using the standard tasks in the Image Reduction and Analysis Facility IRAF.1 The instrumental magnitudes of the RQWLQs and their comparison stars in the image frames were determined by aperture photometry technique (Stetson 1992, 1987), using the Dominion Astronomical Observatory Photometry II (DOMPHOT II).2

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1 Image Reduction and Analysis Facility (http://iraf.noao.edu/)
2 Dominion Astrophysical Observatory Photometry

The aperture photometry was carried out for four values of aperture radii, 1 × FWHM, 2 × FWHM, 3 × FWHM and 4 × FWHM. Seeing disc radius (≡FWHM/2) for each CCD frame was determined by averaging over five adequately bright stars present within each CCD frame. While the photometric data using the different aperture radii were found to be in good agreement, the best S/N was almost always found with aperture radius of 2 × FWHM. Hence, we adopted it for our final analysis.

To derive the Differential Light Curves (DLCs) of a given target RQWLQ, we selected two steady comparison stars present within the CCD frames, on the basis of their proximity to the target source, both in location and apparent magnitude. Coordinates of the comparison stars selected for each RQWLQ are given in Table 2. The g − r colour difference for our ‘quasar–star’ and ‘star–star’ pairs is always <1.5, with a median value of 0.56 (column 7, Table 2). Detailed analyses by Carini et al. (1992) and Stalin et al. (2004b) have shown that colour difference of this magnitude should produce a negligible effect on the DLCs as the atmospheric attenuation varies over a monitoring session.

Since the selected comparison stars are non-varying, as judged from the steadiness of the star–star DLCs, any sharp fluctuation confined to a single data point was taken to arise from improper removal of cosmic rays, or some unknown instrumental effect, and such outlier data points (deviating by more than 3σ from the mean) were removed from the affected DLCs, by applying a mean clip algorithm. In practice, such outliers were quite rare and never exceeded two data points for any DLC, as displayed in Fig. 1.

4 STATISTICAL ANALYSIS OF DLCs

For checking the presence of INOV in a DLC, C-statistic (Jang & Miller 1997) has been the most commonly used test. Although the ‘one-way analysis of variance’ (ANOVA) is the most powerful test for this purpose, it requires a longer data train than is usually present in the available DLCs (de Diego 2010). In our analysis we have not used the C-test since, as pointed out by de Diego (2010), the C-statistics, which is based on ratio of standard deviations is not a reliable test for INOV. This is because: (i) C is not a linear operator, (ii) the commonly adopted critical value (C = 2.576) is too conservative (de Diego 2010). At the same time, the ANOVA test was not found feasible since most of our DLCs contains no more than 40 data points. Therefore, we have based our statistical analysis on the F-test which employs the ratio of variances as, F = variance(observed)/variance(expected) (de Diego 2010), with its two versions: (i) the standard F-test (hereafter F-test; Goyal et al. 2012), and (ii) scaled F-test (hereafter F-test; Joshi et al. 2011). F-test is mainly used in cases when a large magnitude difference is present between the target object and the available comparison stars (Joshi et al. 2011). Except in Paper I, we have adopted F-test since for all our RQWLQs, we have got comparison stars fairly close in apparent magnitude to the target object. An additional advantage of employing the F-test is that our results for RQWLQs can be readily compared with those available in the recent literature for other AGN classes (Goyal et al. 2013). A point worth

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3 Recently, de Diego (2014) has introduced an improved version of the F-test, called enhanced F-test, which includes data for several comparison stars, in order to enhance the power and reliability of the F-test. Here we have limited to the F-test, in order to facilitate comparison with other AGN classes, as mentioned above. The results for our entire INOV data set for RQWLQs, based on the enhanced F-test, will be presented elsewhere.
emphasizing here is that while applying the $F^3$-test, it is especially important to use the correct rms errors on the photometric data points. It has been found that the magnitude errors returned by the routines in the data reduction software packages of \textsc{daophot} and \textsc{iraf}, are normally underestimated by a factor $\eta$ ranging between 1.3 and 1.75, as shown in various studies (e.g. Gopal-Krishna et al. 1995; Garcia et al. 1999; Sagar et al. 2004; Stalin et al. 2004a; Bachev, Strigachev & Semkov 2005). Recently Goyal et al. (2012) estimated the best-fitting value of $\eta$ to be 1.5. Following them, $F^3$-test can be expressed as

$$F_1^3 = \frac{\sigma^2_{(q-s_1)}}{\eta^2 (\sigma^2_{(q-s_1)})}, \quad F_2^3 = \frac{\sigma^2_{(q-s_2)}}{\eta^2 (\sigma^2_{(q-s_2)})}, \quad F_{12}^3 = \frac{\sigma^2_{(q-s_2)}}{\eta^2 (\sigma^2_{(q-s_2)})},$$

(1)

where $\sigma^2_{(q-s_1)}$, $\sigma^2_{(q-s_2)}$ and $\sigma^2_{(q-s_2)}$ are the variances of the ‘quasar–star1’, ‘quasar–star2’ and ‘star1–star2’ DLCs and $\eta$ is the scaling factor and is taken to be 1.5 from Goyal et al. (2012), as mentioned above.

The $F^3$-test is applied by calculating the $F$-values using equation (1), and then comparing them with the critical $F$-value, $F_{99\,\%}$, where $\alpha$ is the significance level set for the test, and $\nu_{99}$ and $\nu_{95}$ are the degrees of freedom for the ‘quasar–star’ and ‘star–star’ DLCs. Here, we set two significance levels, $\alpha = 0.01$ and 0.05, which correspond to confidence levels of greater than 99 and 95 per cent, respectively. If $F$ is found to exceed the critical value adopted, the null hypothesis (i.e. no variability) is discarded to the corresponding level of confidence. Thus, we mark an RQWLQ as \textit{variable} (V) if $F$-value is found to be $\geq F_99(0.99)$ for both its DLCs, which corresponds to a confidence level $\geq 99$ per cent, \textit{non-variable} (NV) if any one of two DLCs is found to have $F$-value $\leq F_95(0.95)$. The remaining cases are designated as \textit{probably variable} (PV).

The inferred INOV status of the DLCs of each RQWLQ, relative to two selected comparison stars, is presented in Table 3. In the first four columns, we list the name of the RQWLQ, date of its monitoring, duration of monitoring, and the number of data points ($N$) in the DLC. The next two columns give the computed $F$-values and the corresponding INOV status of the two DLCs of the RQWLQ, as inferred from the application of the $F^3$-test (see above). Column 7 gives the photometric error $\sigma_{err}(q-s)$ averaged over the data points in the ‘quasar–star’ DLCs (i.e. mean value for $q-s_1$ and $q-s_2$).
Figure 1. Differential light curves (DLCs) for the six RQWLQs from our sample. The name of the RQWLQ together with the date and duration of its monitoring are given at the top of each panel. In each panel the upper DLC is derived using the two non-varying comparison stars, while the lower two DLCs are the ‘quasar–star’ DLCs, as defined in the labels on the right side. Apparently outlier point (at >3σ) in the DLCs are marked with crosses and those points have been excluded from the statistical analysis.

$q = s^2$ DLCs, which typically lies between 0.02 and 0.07 mag (without the $\eta$ scaling mentioned above). The last column gives the peak-to-peak amplitude $\psi$ of INOV, as defined by Romero, Cellone & Combi (1999),

$$\psi = \sqrt{(D_{\text{max}} - D_{\text{min}})^2 - 2\sigma^2}$$ \hspace{1cm} (2)

with $D_{\text{min, max}}$ = minimum (maximum) values in the RQWLQ DLC and $\sigma^2 = \eta^2(\sigma^2_q + s^2)$, where $\eta = 1.5$ (Goyal et al. 2012).

We have computed the INOV duty cycle (DC) for our RQWLQ sample using the definition of Romero et al. (1999),

$$\text{DC} = 100 \frac{\sum_{i=1}^{n} N_i(1/\Delta t_i)}{\sum_{i=1}^{n}(1/\Delta t_i)} \text{ percent},$$ \hspace{1cm} (3)
where $\Delta t_i = \Delta t_{\text{obs}}(1 + z)^{-1}$ is duration of the monitoring session of an RQWLQ on the $i$th night, corrected for its cosmological redshift, $z$. Since the duration of the observing session for a given RQWLQ differs from night to night, the computation of DC has been weighted by the actual monitoring duration $\Delta t_i$ on the $i$th night. $N_i$ was set equal to 1, if INOV was detected (i.e. ‘V’ for both DLCs on the night), otherwise $N_i$ was taken as 0.

### 5 RESULTS AND DISCUSSION

This work together with Paper I and Paper II allows us to determine the INOV characteristics of RQWLQs using the entire set of 15 bona fide RQWLQs covered in our programme launched about two years ago. This is the first investigation of the INOV properties of radio-quiet weak emission line quasars and is targeted on their subset classified in the literature as good candidates for radio quiet BL Lacs. For the entire set we have got 30 DLCs which are continuous and have a duration exceeding 3.5 h in all except one case where the duration is 3.0 h (average duration of the 30 DLCs being 4.2 h, see Table 4 and Section 3.1). Our INOV results are based on the $F^\psi$-test, which is not only more reliable in comparison to other feasible tests (Section 4), but also offers an additional advantage in that our INOV results for the RQWLQs can be directly compared with those reported in recent literature for other prominent AGN classes (see below).

The INOV results reported in Papers I and II were based on a set of 10 RQWLQs with 19 DLCs, yielding INOV DC of 4 per cent. In this study, we have been able to significantly enlarge the INOV data base as we now have 30 DLCs covering our entire set of 15 RQWLQs. The INOV DC for the entire set is found to be $\approx$5 per cent (using $F^\psi$-test). In order to ascertain the effect of likely uncertainty in the adopted value of $\eta$, we have repeated the computation of INOV DC for the 30 DLCs of RQWLQs, setting two extreme values for $\eta$ ($=1.3$ and $1.75$) reported in the literature (Goyal et al. 2012, and references therein). The INOV DCs computed for these extreme values of $\eta$ are still 5 per cent. Thus, the $F^\psi$-test is found to give a consistent result over the maximum plausible range in $\eta$.

It is interesting to compare our DC estimates for RQWLQs with those recently reported by GGWSS13 for several prominent AGN classes, again using the $F^\psi$-test with $\eta$ set equal to 1.5. INOV DC estimated in their study is $\approx$10 per cent (6 per cent) for RQQs, $\approx$18 per cent (11 per cent) for radio-intermediate quasars (RIQs), $\approx$5 per cent (3 per cent) for radio lobe-dominated quasars (LDQs), $\approx$17 per cent (10 per cent) for radio core-dominated quasars with low-optical polarization (LPCDQs), $\approx$43 per cent (38 per cent) for radio core-dominated quasars with high-optical polarization (HPCDQs) and $\approx$45 per cent (32 per cent) for BLOs (the values inside parentheses refer to the DLCs showing INOV amplitude $\psi < 3$ per cent). Thus, the DC of strong INOV ($\psi > 3$ per cent) found here for RQWLQs is similar to those reported (with $\psi > 3$ per cent) for RQQs, RIQs, LDQs and LPCDQs, while HPCDQs and BLOs have distinctly higher DC. However, this comparison is not strictly valid, given the fact that in the observations of all these other AGN classes (GGWSS13), an INOV detection threshold ($\psi_{\text{lim}}$) of 1–2 per cent had typically been achieved. Being 1–2 mag fainter, the INOV detection threshold reached for the present set of RQWLQs is less deep ($\psi_{\text{lim}} \approx 5$ per cent, Table 4). Thus, while making comparison with the above-mentioned other AGN classes, our present estimate of INOV DC for RQWLQs ($\approx$5 per cent) may be treated as a lower limit. This cautionary remark is underscored by the fact that both events of INOV detection reported here (Table 4) are marked by extremely large amplitudes ($\psi \approx 30$ per cent peak-to-peak, occurring on hour-like time-scale), rivaling blazars in their highly active phases (e.g. Sagar et al. 2004; Gopal-Krishna et al. 2011; Goyal et al. 2012). Clearly, it would be very interesting to check if a factor of 2–3 improvement in $\psi_{\text{lim}}$ would reveal many more events of INOV among RQWLQs, yielding a statistically robust estimate for the DC of strong INOV ($\psi > 3$ per cent) for RQWLQs, which is distinctly higher than the present estimate of $\approx$5 per cent, perhaps even approaching the high values established for blazars.

To summarize, the twin objectives pursued in our INOV study of RQWLQs are (a) to find cases of very strong INOV ($\psi$ well above 3 per cent), any such RQWLQs would be outstanding candidates for the putative radio-quiet BL Lacs, and (b) to quantify the INOV DC for RQWLQs, in both strong and weaker INOV regimes. With a significantly enlarged sample of 30 DLCs of RQWLQs in the present study, we now find that their INOV DC is about 5 per cent, at a typical INOV detection threshold of around 5 per cent and a monitoring duration of about 3–5 h. In our programme, two of the RQWLQs were found in two sessions to exhibit very strong INOV (amplitude $\psi > 10$ per cent), a level never observed in our 2-decade

| RQWLQ | Date (dd.mm.yyyy) | $T$ (h) | $N$ | $F$-test values | INOV status | INOV amplitude $\psi_1$ ($\%$) | $\psi_2$ ($\%$) |
|-------|-------------------|---------|-----|-----------------|-------------|-----------------------------|-------------|
| J081250.79+522531.0 | 01.01.2014 | 3.59 | 31 | 0.43, 0.73 | NV, NV | 0.02 | 3.43, 5.74 |
| J081250.79+522531.0 | 02.01.2014 | 3.46 | 30 | 0.38, 0.43 | NV, NV | 0.02 | 2.98, 4.40 |
| J090843.25+285229.8 | 01.02.2014 | 4.69 | 39 | 0.46, 0.56 | NV, NV | 0.03 | 8.29, 7.88 |
| J090843.25+285229.8 | 02.02.2014 | 4.29 | 36 | 0.62, 0.58 | NV, NV | 0.07 | 30.39, 23.85 |
| J090843.25+285229.8 | 01.04.2014 | 4.92 | 42 | 0.50, 0.71 | NV, NV | 0.03 | 6.23, 8.95 |
| J134601.29+585820.1 | 01.04.2014 | 4.21 | 36 | 0.48, 0.51 | NV, NV | 0.02 | 4.18, 4.52 |
| J140710.22+241853.6 | 03.05.2014 | 3.00 | 23 | 4.19, 4.37 | NV, NV | 0.05 | 37.24, 36.73 |
| J141200.04+634414.9 | 04.05.2014 | 4.56 | 37 | 0.40, 0.26 | NV, NV | 0.04 | 10.28, 5.75 |
| J160410.22+432614.7 | 05.05.2014 | 4.62 | 38 | 1.01, 1.01 | NV, NV | 0.04 | 26.05, 24.60 |
| J160410.22+432614.7 | 30.05.2014 | 4.32 | 37 | 1.08, 1.11 | NV, NV | 0.04 | 17.61, 15.52 |

Notes. $^a$V = variable, i.e. confidence level $\geq$0.99; PV = probable variable, i.e. 0.95–0.99 confidence level; NV = non-variable, i.e. confidence level $<0.95$. Variability status inferred, $F^\psi$ values and INOV peak-to-peak amplitudes $\psi$ using the quasar–star1 and quasar–star2 DLCs are separated by a comma.

Table 3. Observational details and INOV results for the set of 6 RQWLQs monitored in 11 sessions (this work).
long INOV programme (Stalin et al. 2004a; Goyal et al. 2012; GGWSS13) except for BL Lacs and HCDQs. The two RQWLQs, namely J090843.25+285229.8 ($\psi \sim 31$ per cent on 10.02.2013, Table 4) and J140710.26+241853.6 ($\psi \sim 36$ per cent on 03.05.2014, Fig. 1, and Table 4), are thus currently the best available candidates for the elusive population of radio-quiet BL Lacs and hence need to be followed up.

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