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Intranight optical variability in optically selected QSOs

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ABSTRACT

We report results from a continuing programme to search for intranight optical variability in one radio-moderate and six radio-quiet (but all optically bright and luminous) quasi-stellar objects, using the 2.34-m Vainu Bappu Telescope. Our data clearly show microvariability for the radio-moderate QSO, 0838 + 359, and provide strong indications of microvariability for two of the radio-quiet QSOs, 0946 + 301 and 1049 − 006, and possibly also for a third, 1206 + 459. Additional observations of these and other QSOs could provide a powerful means of discriminating among various theoretical mechanisms proposed for the energy source and, in particular, the origin of optical microvariability in active galactic nuclei. These apparent detections of microvariability in radio-quiet QSOs seem to favour models where flares on accretion discs are responsible for the microvariability.

Key words: accretion, accretion discs – galaxies: active – galaxies: photometry – quasars: general.

1 INTRODUCTION

With the use of CCD cameras as N-star photometers, optical fluctuations of 1–2 per cent on time-scales of a few hours (microvariability) are now known to be typical of BL Lacertae objects and optically violent variable (OVV) quasars (e.g. Miller, Carini & Goodrich 1989; Carini 1990; Carini et al. 1991, 1992; Miller et al. 1992; Wagner 1992). Many of these blazars also show significant intraday variability in the centimetre radio band (e.g. Quirrenbach et al. 1989; Krichbaum, Quirrenbach & Witzel 1992; Quirrenbach et al. 1992). Often, the radio variations seem to show a preference for day-like time-scales (Heeschen 1984; Quirrenbach et al. 1989, 1992). So far, ultraviolet microvariability has been confirmed for only one source, PKS 2155 − 304, where the *IUE* UV flux was observed to change by ~ 10 per cent in 1 d (Edelson et al. 1991; Miller et al. 1992; Urry et al. 1993). Seyfert galaxies and other active galactic nuclei (AGN) have long been known to show substantial variability on time-scales much less than 1 d in the X-ray band (e.g. Lawrence et al. 1987; McHardy 1989). However, no systematic searches for optical microvariability in radio-quiet quasi-stellar objects (RQQSOs) were performed until we examined two southern RQQSOs, 0530 − 37 and 0540 − 38 (Gopal-Krishna, Wiita & Altieri 1992). The beginning of the current study examined five northern RQQSOs (Gopal-Krishna, Sagar & Wiita 1993, hereafter Paper I), but no clear evidence of flux variations down to the ≈ 2–3 per cent level was found over the course of a night for any of those objects, although hints of microvariability were found for three of them. Further results of the monitoring programme, based on a much denser temporal coverage, are reported in the present study.

Theoretical explanations of microvariability can be divided into extrinsic and intrinsic categories. One extrinsic mechanism is refractive interstellar scintillations, although they are only relevant in the radio band. While a statistical analysis of radio fluctuations of an entire sample of compact flat-spectrum radio sources is consistent with interstellar scintillations always being present (Quirrenbach et al. 1992; also, Shapirovskaya et al. 1995), this mechanism is unable to account for the observed simultaneity and similar amplitude of the variations over a large range of radio frequencies seen in roughly one quarter of them (Qian et al. 1991; Quirrenbach et al. 1992). Another extrinsic mechanism is superluminal microlensing (Gopal-Krishna & Subramanian 1991; Subramanian & Gopal-Krishna 1991), which can explain many of the features of rapid variations at different wavelengths; however, its statistical likelihood is at present not clear, and hence this possibility will not be explored here. We

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note, however, that Hawkins (1993) has argued that microlensing by a cosmologically significant population of substellar objects is a plausible way to account for the bulk of the slow (multiyear) variations recorded in the optical monitoring of QSOs (e.g. Smith, Leacock & Webb 1988). The extremely high brightness temperatures ($\sim 10^{21}$ K) inferred from the variability of the blazar PKS 0537 − 441 by Romero, Combi & Colomb (1994) could be explained by the superluminal microlensing, or by the coherent processes mentioned below.

One family of intrinsic explanations is based on a relativistic shock propagating down a jet and interacting with irregularities in the flow (Qian et al. 1991; Marscher, Gear & Travis 1992), or relativistic shocks whose direction to the line of sight is variable (Gopal-Krishna & Wiita 1992). These are motivated by apparent superluminal motions and the success of shock-in-jet models in explaining the large radio flares observed on year-like time-scales (e.g. Hughes, Aller & Aller 1991). A related model involves non-axisymmetric bubbles carried outwards in relativistic magnetized jets (Camenzind & Krockenberger 1992). Plasma processes, both incoherent (Krishan & Wiita 1994) and coherent (Baker et al. 1988; Benford 1992; Krishan & Wiita 1990, 1994; Lesch & Pohl 1992), might also play important roles, but nearly all of these models also incorporate relativistic jets or electron beams. The correlation between spectral shape and intensity changes in the blazar PKS 2155 − 304 argues in favour of jet models for UV and optical variations in this case (Urry et al. 1993). Another family of intrinsic explanations invokes numerous flares or hotspots on the surface of (or corona above) the accretion disc believed to surround the central engine (Wiita et al. 1991, 1992; Chakrabarti & Wiita 1993; Mangalam & Wiita 1993); a similar model has been independently proposed to explain rapid X-ray variations of blazars (e.g. Abramowicz et al. 1991; Zhang & Bao 1991). The hypothesis that a large coronal flare near an accretion disc produced the peculiar nuclear radio structure of 3C 147 has recently been propounded (Chu et al. 1993).

In that most radio-quiet AGN are thought not to eject relativistic jets (e.g. Antonucci, Barvainis & Alloin 1990; Terlevich, Melnick & Moles 1987), unlike blazars where jets are expected to dominate the emission (e.g. Bregman 1991; Urry & Padovani 1991), any evidence for microvariability in radio-quiet QSOs would provide substantial support for the hotspot on accretion disc models. It should be noted that Miller, Rawlings & Saunders (1993) point out that some RQQSOs, when examined very carefully in the radio, do show evidence for jets (see, also, Kellermann et al. 1994). Yet the fact that RQQSOs generally lie on the far-IR versus radio correlation defined for disc galaxies (Sopp & Alexander 1991) would suggest that star formation plays an important role in their radio emission. Additional indirect evidence for the idea that RQQSOs lack significant jets is that every one of the first 26 AGN γ-ray sources detected by the EGRET instrument on the *Compton Gamma-Ray Observatory* were radio-loud (e.g. Bregman 1994). The very strong correlation between radio and γ-ray emissions implies that some mechanism similar to inverse Compton scattering (e.g. Schlickeiser & Dermer 1994), very possibly related to shocks in relativistic jets, is important for radio-loud AGN (Bloom & Marscher 1993), but does not seem to be very relevant for RQQSOs. An interesting new proposal is that all AGN emit jets from their discs, but that radio-loud sources have very strong jets (as a fraction of disc luminosity) whose electron energy distributions have low energy cut-offs at Lorentz factors above ~ 100, while radio-quiet sources have weaker jets with electrons moving with much lower Lorentz factors (Falcke & Biermann 1995; Falcke, Malkan & Biermann 1995). Falcke et al. propose that radio-loud sources may require an electron–positron plasma in their jets, perhaps produced at high energies through proton–proton collisions, while radio-weak sources function with electron–proton plasma originating from a thermal pool by shock acceleration. Despite this uncertainty, it is clear that, as far as optical emission is concerned, jets can play an important role in radio-loud quasars but in RQQSOs direct disc emission (e.g. Sun & Malkan 1989) may be more important, at least within the models characterized by a compact supermassive central engine.

So far, nearly all quasars searched for microvariability in the optical or radio have been core-dominated radio-loud sources that were already known to vary by large amounts over longer time-scales. A few Seyfert galaxies have been monitored using CCD detectors as N-star photometers, usually with negative results; this lack of detection of variations, however, could easily be due to the short durations of most of these observations (H. R. Miller, private communication). The best evidence so far is for Akn 120 (0513 − 002), which showed ~ 0.04 mag fluctuations over a 5-h period (Miller & Noble 1994; Noble et al. 1994). Akn 120 is a radio-weak Seyfert with $F_{1.5\,\mathrm{GHz}} = 8.05 \pm 1.50$ mJy and $z = 0.033$ (Barvainis & Antonucci 1989). Claims for optical microvariability in the Seyferts NGC 4151 (Lyutyi et al. 1989) and NGC 7469 (Dultzin-Hacyan et al. 1992) have been made, but, as discussed in Paper I, these objects have radio-loud cores, as well as a substantial contamination in the visible from the host galaxy, and so do not provide clear tests. The objects XX Ceti and US 3215, originally thought to be stellar, and possibly cataclysmic variables, have now been recognized to be AGN which have shown marginal evidence of intranight optical variability (Howell & Usher 1993); however, their radio properties are unknown to us.

As argued in some detail in Paper I, the most secure test of the accretion disc model for intranight variation would come from optical (usually corresponding to rest-frame blue or UV) monitoring of radio-quiet, but optically powerful and distant (hence, point-like) QSOs, using wide-field CCD arrays which would encompass a set of several suitable comparison stars on each frame. Here, we present new results from such an ongoing programme.

2 OBSERVATIONS

The QSOs we examined were chosen from the lists of Hewitt & Burbidge (1993) and Véron-Cetty & Véron (1993) by the following criteria: (i) $M_V \ll -23$, so that we are definitely dealing with luminous QSOs and not Seyfert galaxies (Kellermann et al. 1989); (ii) radio flux at 5 GHz less than 0.5 mJy (Kellermann et al. 1989, 1994), so that these objects are indeed radio-quiet and are thus unlikely to have a significant fraction of their emission emanating from any jets (but see below for 0838 + 359); (iii) $m_V \approx 16$, bright enough to allow good signal-to-noise ratios to be attained in exposures of

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~ 10 min; (iv) at least two, and preferably three, adequately bright stars could be located within the CCD frame encompassing the QSO, thus allowing us to identify and discount any of the comparison stars that were themselves variable on short time-scales; (v) right ascension in the range that would allow monitoring for at least 6 h during a night, roughly equally distributed around the meridian so as to minimize airmass-induced extinction.

The observations described here were carried out on the nights of 1993 January 23–26, February 26, 27, April 21–23 and May 15–17 in the V and R photometric passbands, using a blue-coated Astromed GEC P8603 CCD detector at the f/3.23 prime focus of the 2.34-m Vainu Bappu Telescope located at the Vainu Bappu Observatory (VBO), Kavalur, India. This CCD chip has 385 × 578 pixel of 22 microns square; each pixel thus corresponds to a 0.64-arcsec square on the sky and the total area covered by a CCD frame is about 4 × 6 arcmin^2. The readout noise for the system was about 8 electrons per pixel, and the electrons per ADU was equal to 4. Bias and dark frames were taken intermittently. In order to be able to detect small fluctuations reliably we carried out differential photometry, generally ensuring that the locations of the QSO and stellar objects did not change by more than a few pixels from exposure to exposure. This largely obviated the need to flat-field the frames, which introduces additional noise.

We monitored the objects QQ 0838 + 359, 0946 + 301, 1049 − 006, 1206 + 459, 1352 + 011, 1522 + 102 and 1630 + 377 in the V and R bands for between one and four nights for periods up to ~ 8 h. Table 1 gives the redshifts, nominal m_V and M_V values, and dates of observations, along with which bands were used on which nights; it also summarizes our conclusions as to the microvariability status of each QSO. A cosmology with $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ was assumed to compute the absolute magnitudes. Integration times varied from 7 to 15 min per exposure, depending upon the filter used and the transparency of the sky. These exposures yielded signal-to-noise ratios (S/N) for the QSOs between 50 and 150. At least one frame in the R was taken during the V-band observations and at least one frame in the V was taken during the R-band observations, so as to provide relative colour information, and at least one B measurement was also usually taken. The seeing was typically 2–3 arcsec, adequate to provide accurate relative magnitudes for point-like sources.

The data were reduced at the VBO VAX 11/780 system using the DAOPHOT software package and the COMTAL Vision image display station. Photometry of the QSOs on the data frames was carried out using concentric circular apertures of ~ 7-, 10- and 13-arcsec diameter centred on the objects. The background was subtracted using the measured counts in annuli around the circular apertures. After careful analysis it was determined that the best S/N and the most reliable measurements could be obtained using the ~ 7-arcsec aperture; these are therefore presented below. For each frame, three comparison stars were also reduced in a manner identical to that of the QSO, with the exception of 1206 + 459, for which only two useful comparison stars were available.

The separations and orientations of the comparison stars with respect to the QSOs (based on the finding charts given in Schmidt & Green 1983) are given in Table 2. The differences in colour indices betwen the QSO and each of the comparison stars are also given in Table 2. For the two QSOs common to both Paper I and this work, the comparison stars are not, in general, defined identically, as the QSO positions on the chip were adjusted in an attempt to provide better comparison stars. As discussed in Paper I, the differential photometry is unlikely to be significantly affected by convolution of the filter response with the spectral differences between the QSOs and stars, because of the relatively small colour index differences (see Carini 1990); the two cases where this may be a problem are mentioned specifically below.

3 RESULTS

Figs 1–7 display the magnitude differences versus time (difference light curves: DLCs), as determined from the observations described above. The photometric errors have been estimated using the artificial 'star add' experiment given in the DAOPHOT software package. The difference between the magnitudes of the added and recovered stars was assumed to be the error in our photometric data. A comparison of these errors with the formal errors returned by the DAOPHOT software package indicates that the formal errors returned by the DAOPHOT package are too small by a factor of 1.75. Accordingly, the error bars drawn in Figs 1–7 for each data point were determined by adding in quadrature 1.75 times the formal 1σ errors for the fluxes of the main object and the comparison object, as given by the DAOPHOT package.

In considering the likelihood that fluctuations are real, we adopt the stringent, though commonly used (cf. Romero et al. 1994 and references therein), statistical criterion of Keste-

Table 1. Monitoring of QSOs.

QSO	z	m_V	M_V	Dates of Observations and Filter	Microvariable
0838+359	1.775	16.	−30.1	23,24,25,26 Jan 93; 27 Feb 93 (V)	Yes
0946+301	1.216	16.38	−28.6	24,25,26 Jan 93 (V); 17 May 93 (R)	Very likely
1049−006	0.357	16.04	−25.8	26 Feb, 23 Apr 93 (V)	Likely
1206+459[a]	1.158	16.07	−28.8	26,27 Feb (V); 23 Apr 93 (R)	Possible
1352+011[a]	1.121	16.04	−28.7	21 Apr 93 (R)	No
1522+102	1.321	15.65	−29.6	22 Apr 93 (R)	No
1630+377	1.466	16.07	−29.5	15,16,17 May 93 (R)	No

[a]Additional data is in Paper I.

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Table 2. Comparison stars.

QSO	Star 1				Star 2				Star 3			
	Δr(″)	PA(°)	B−V	V−R	Δr(″)	PA(°)	B−V	V−R	Δr(″)	PA(°)	B−V	V−R
0838+359	135	293	0.61	0.19	180	52	0.12	−0.04	170	85	0.32	0.05
0946+301	46	166	0.23	0.02	84	259	0.46	0.14	201	324	...	...
1049−006	235	110	0.43	0.02	101	146	0.37	0.09	90	182	0.19	0.09
1206+459	271	255	...	0.05	158	238	0.33	0.10	...	...	...	...
1352+011	113	24	0.54	0.59	135	343	0.29	0.23	130	327	0.23	0.13
1522+102	233	91	...	0.37	186	67	...	0.26	110	194	...	−0.01
1630+377	124	68	...	0.03	124	36	...	0.06	107	152	...	0.00

Note. The columns headed $B-V$ and $V-R$ refer to the differences of the stars' colour indices from those of the corresponding RQQSO.

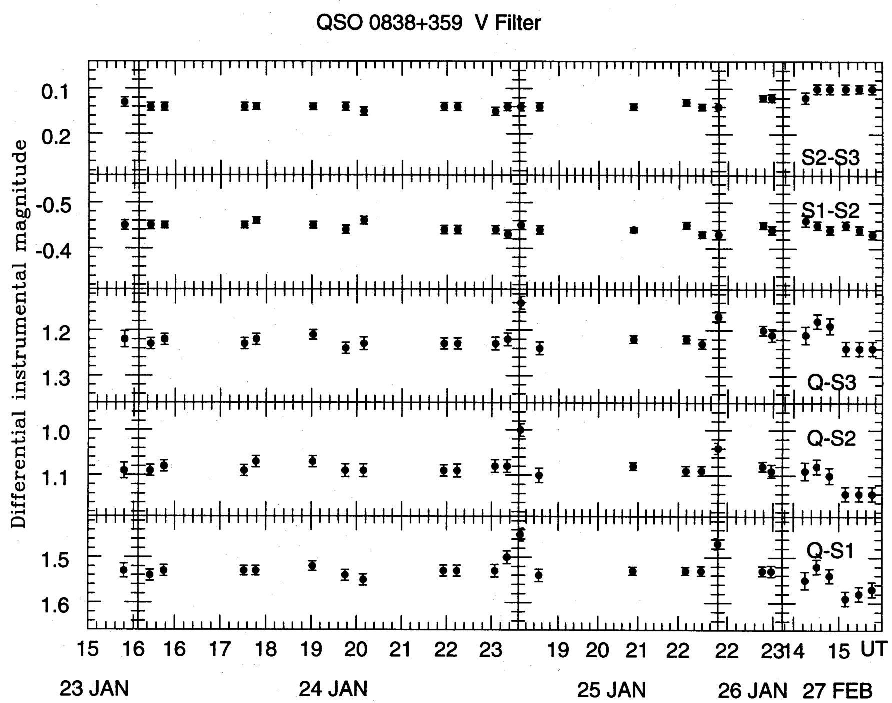

Figure 1. *V*-band observations for the QSO 0838 + 359. Starting from the bottom panel, differential light curves are presented for the QSO with respect to stars 1, 2 and 3; similar curves are also given for the differences between stars 1 and 2, and stars 2 and 3.

van, Bridle & Brandie (1976): if $P(\chi^2) > 0.999$ we can absolutely claim to have seen variability, but we consider a source with $P(\chi^2) < 0.995$ to be formally non-variable. Even though in some cases an individual DLC for a star might show small, albeit statistically significant, variations during a night, temporally correlated variations on other DLCs involving the same star are usually not observed. Hence the formal statistical significance of the variations found in the few such cases involving stars alone (discussed below) might often be due to a slight underestimation of the error bars. For instance, an average increase of the error bars of the DLCs by a factor of 1.2 always reduces the stellar variations to an insignificant level ($P < 0.99$). Of course, in a few cases, specifically noted below, it is likely that one or more of the comparison stars did genuinely vary, since such variations can be seen in more than one DLC. Therefore a more compelling evidence for intranight variability for either a QSO or a star would be provided by correlated variations (both in time and amplitude) seen on different DLCs involving that particular object.

We now discuss the results for each source individually.

0838 + 359. This was the only non-PG quasar in our list, so that accurate radio fluxes were not known. To check if it satisfied criterion (ii) of Section 2, we were able to obtain VLA[1] maps, though only after the optical monitoring.

[1]The Very Large Array is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities Inc., under contract with the National Science Foundation.

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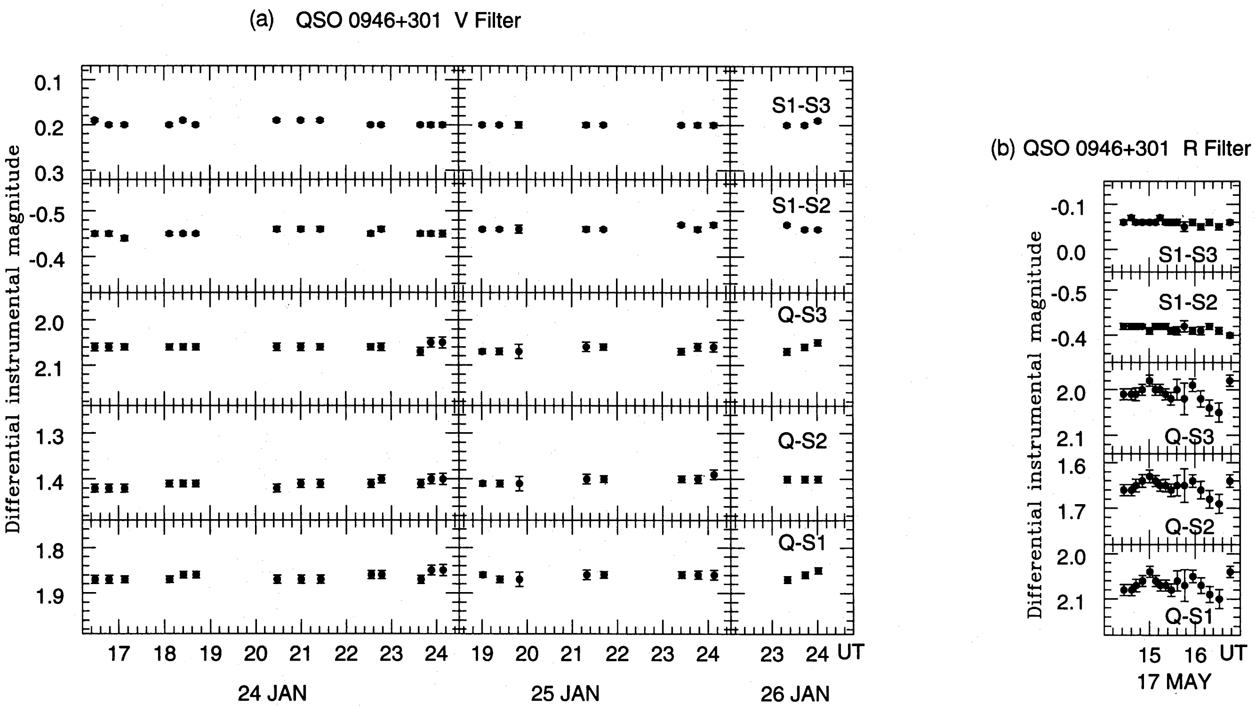

Figure 2. (a) V-band observations for QSO 0946 + 301. As Fig. 1, except that the upper panel is a comparison of the magnitudes of stars 1 and 3. (b) R-band observations for 0946 + 301.

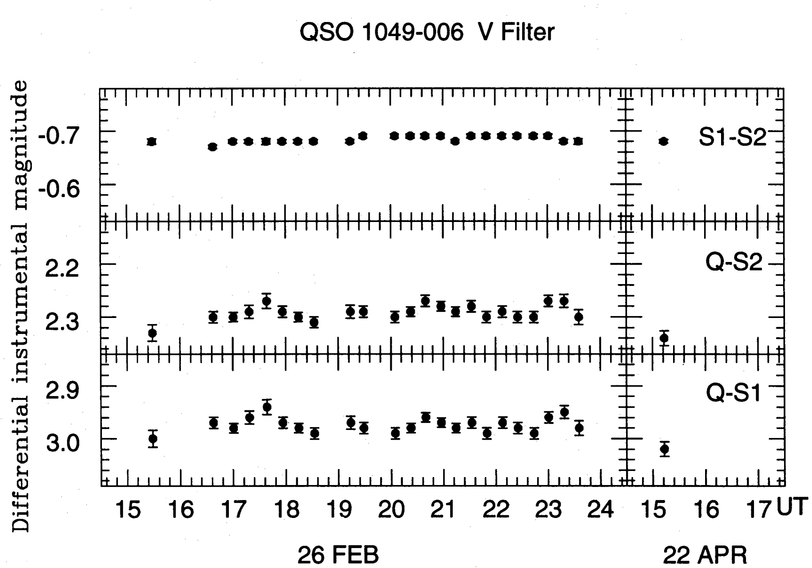

Figure 3. V-band differential light curves for QSO 1049 − 006; only differences between Q and 1 and Q and 2, and stars 1 and 2 are presented.

Instead of confirming radio quietness, which has ~85 per cent *a priori* probability, these measurements revealed a weak, compact flat-spectrum radio source with flux densities of 6.2 ± 0.8 mJy at 1.4 GHz and 6.0 ± 0.4 mJy at 8.4 GHz located at a position of $\alpha_{1950} = 08^{h}38^{m}07^{s}.43$, $\delta_{1950} = +35°55'21''.9$, which coincides with the optical position (Véron-Cetty & Véron 1993). So, alone among this sample, this QSO is not strictly radio-quiet. The ratio, R, however, of the radio-to-optical flux densities of this QSO is ~5, which is below the limiting value of 10 usually considered to be the borderline between the radio-loud and radio-quiet quasar populations (Kellermann et al. 1989). Thus, while on this basis it may be formally classified as radio-quiet, the detected flat-spectrum radio core is probably manifesting the relativistic jet phenomenon.

As can be seen from Fig. 1, on three nights (1993 January 24 and 25 and 1993 February 27) we had at least six measurements for this source taken in the V band. For the

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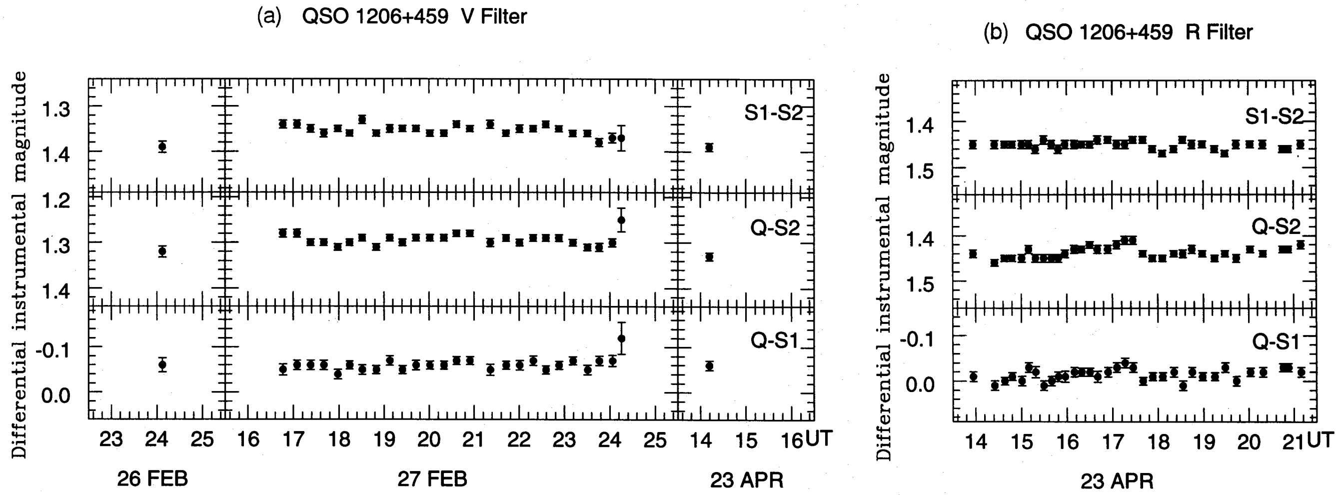

Figure 4. (a) As Fig. 3, for *V*-band observations for QSO 1206 + 459. (b) *R*-band observations for QSO 1206 + 459.

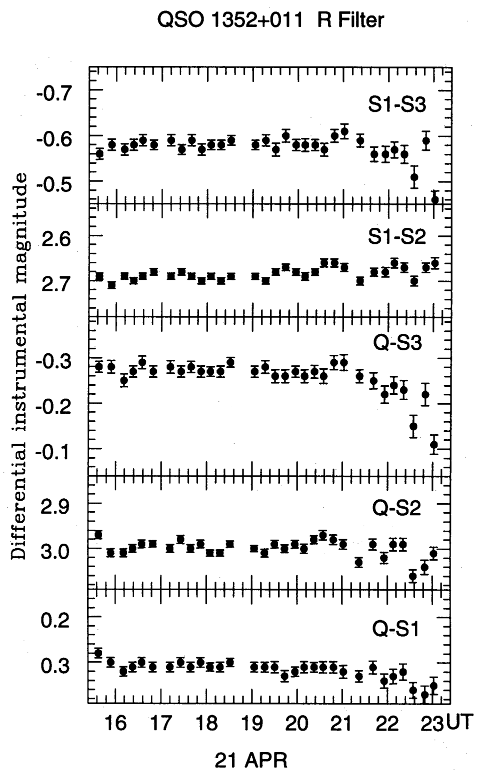

Figure 5. Differential light curves in the *R* band for QSO 1352 + 011, with the comparisons as in Fig. 2.

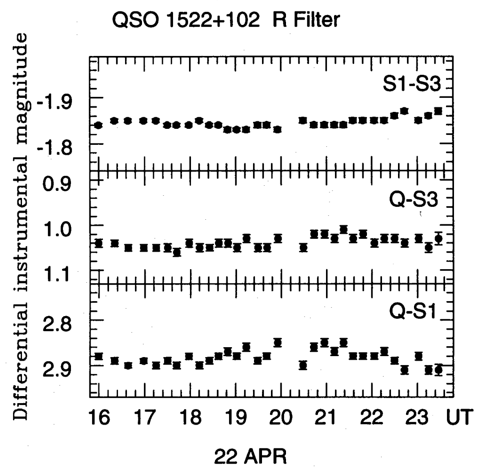

Figure 6. *R*-band differential light curves for QSO 1522 + 102, with the comparisons being between the QSO and stars 1 and 3.

first night there is no significant evidence that the QSO or any star varies, with the highest χ^2 statistic for the DLC between stars 1 and 2 ($P_{Q-1} = 0.422$, $P_{Q-2} = 0.078$, $P_{Q-3} = 0.090$, $P_{1-2} = 0.780$ and $P_{2-3} = 0.007$).

On the night of January 25, we conclude that the QSO varies ($P_{Q-1} = 0.99999$, $P_{Q-2} > 0.99999$ and $P_{Q-3} > 0.99999$), whereas there is no evidence that star 1 does ($P_{1-2} = 0.421$), and stars 2 and 3 are rock-steady ($P_{2-3} = 0.001$). We also note from Table 2 that star 1 is the only one with a large colour index difference from the QSO, but as the other two are close in colours, this colour difference is irrelevant to our conclusion.

The data from February 27 also support the hypothesis that the QSO 0838 + 359 exhibits microvariability despite the lower quality of those data. The apparent rise and fall in the QSO's luminosity between UT 14:10 and 15:01 is marginally statistically significant (P_{Q-3} exceeds 0.99999, but $P_{Q-1} = 0.964$, and $P_{Q-2} = 0.986$, while $P_{1-2} = 0.449$, and $P_{2-3} = 0.111$).

0946 + 301. With a flux density of under 30 μJy at 5 GHz (Kellermann et al. 1994), this QSO is definitely radio-quiet (as are all of the following four QSOs). Our measurements in the *V* band on 1993 January 24 and 25 (Fig. 2a) produced no evidence for variability of this QSO. The formal probabilities on those two dates, respectively, were $P_{Q-1} = 0.117$, 0.105; $P_{Q-2} = 0.098$, 0.327; $P_{Q-3} = 0.034$, 0.163; $P_{1-2} = 0.195$, 0.348; $P_{1-3} = 0.750$, 0.002.

Four months later, the *R*-band monitoring on 1993 May 17 (Fig. 2b) yielded more interesting results, although there

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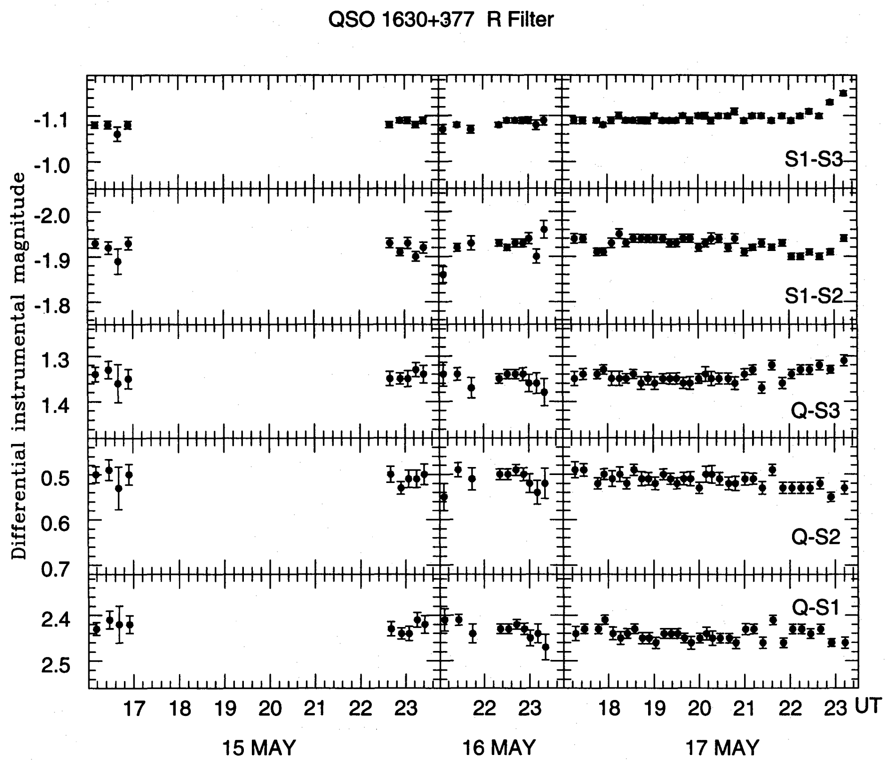

Figure 7. Differential *R*-band light curves for QSO 1630 + 377, with the comparisons as in Fig. 2.

was no statistically significant evidence of variability on any individual DLC for the RQQSO. The formal probabilities for this night were $P_{Q-1} = 0.759$, $P_{Q-2} = 0.346$, $P_{Q-3} = 0.877$, $P_{1-2} = 0.228$ and $P_{1-3} = 0.323$, thanks to the large error bars. None the less, the DLCs for this QSO, relative to each of the three comparison stars, clearly show a rise of ≈ 0.05 mag between 14.6 and 15.0 UT, followed by a decline to the original level at 15.4 UT. This distinct correlation in both time and amplitude is followed immediately by another correlated fluctuation, although the latter data are noisier. No such correlated changes are seen for the DLCs involving the stars alone. Similarly clear correlations are seen when the photometry is repeated using the 10-arcsec aperture. Here, too, the rise and decline of the relative flux are found to occur systematically, i.e. over several consecutive data points.

We thus argue that, despite the lack of formal statistical significance, there is a strong likelihood that the RQQSO 0946 + 301 did indeed exhibit microvariability on one of the three nights it was observed, even though we cannot claim its presence as securely as we can for 0838 + 359.

1049 − 006. Because of the poor quality of the data involving the faint star 3, we only display the comparisons between the QSO and stars 1 and 2 in Fig. 3 for the one night of observations, 1993 February 26. The variation, as determined by the χ^2 statistic, is strongest between the two stars, but none is formally significant, with $P_{Q-1} = 0.870$, $P_{Q-2} = 0.835$ and $P_{1-2} = 0.998$; ($P_{Q-3} = 0.011$ and $P_{1-3} = 0.986$).

The DLCs in Fig. 3, however, show a strong hint of correlated fluctuations of the QSO relative to both bright companion stars throughout the night. The differences between stars 1 and 2 never exceed 0.01 mag; their rather high formal probability of mutual variation is probably due to a slight error underestimation at that level, while the strongly correlated magnitude changes of the QSO relative to both stars reach 0.05 mag peak-to-peak. We take this as a strong hint that microvariability is present in this RQQSO. We have examined the data taken through the 10-arcsec aperture, and these correlated fluctuations remain clearly evident. Still, because of the formally inadequate χ^2 significance and the lack of at least three good comparison stars, we do not claim the detection of intranight variability for this QSO as strongly as we do for 0838 + 359.

1206 + 459. This object showed a hint of microvariability, based on a poorly sampled data set from the 1992 campaign, and so it was remonitored in 1993 for one night with a *V* filter (February 27) and one night with an *R* filter (April 23) with dense temporal coverage. In the *V*-band measurements (Fig. 4a, after discarding the last, very noisy point), there is moderate variability between the QSO and star 2 and between stars 1 and 2, but not between the QSO and star 1 ($P_{Q-1} = 0.156$, $P_{Q-2} = 0.983$, $P_{1-2} = 0.978$). No correlated variability of any type is seen.

An examination of the *R*-band data (Fig. 4b) gives $P_{Q-1} = 0.9958$, $P_{Q-2} > 0.99999$, and $P_{1-2} = 0.740$. This substantial indication of QSO microvariability is supported by the correlated nature of a slow rise by ~ 0.04 mag from 15.5 UT to 17.3 UT, but since we have only two comparison stars and, by our stringent criterion, the QSO variation is formally significant only with respect to star 2, we again can-

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not make a strong claim for the presence of intranight variability; however, this RQQSO clearly demands additional attention, as it has shown consistent hints of microvariability on two occasions.

1352 + 011. This was another RQQSO with a hint of microvariability reported in Paper I, so again we re-examined it with denser temporal coverage, albeit for only one night, 1993 April 21 (Fig. 5). If the entire data set is considered, the formal probability of variation between the QSO and each star and between each star pair exceeds 0.999, but, when we discard the last five, substantially noisier, data points, the χ^2 probabilities become $P_{Q-1}=0.361$, $P_{Q-2}=0.9966$, $P_{Q-3}=0.091$, $P_{1-2}=0.9996$ and $P_{1-3}=0.199$. The analysis is complicated for this object because the differences in colour indices between the QSO and star 1 are substantial. Thus there is no evidence that the QSO varies, while these data support the hypothesis that star 2 does vary. The only clear correlated changes involve the last few noisy points, which, if valid, imply that star 3 may also have varied.

1522 + 102. Here, the data involving star 2 lacked enough S/N to be able to provide useful information, and so Fig. 6 presents the *R*-band data taken on 1993 April 22 only for the QSO and stars 1 and 3. The probabilities of variations between the QSO and star 1, the QSO and star 3, and stars 1 and 3 are all nominally significant, with $P_{Q-1}>0.99999$, $P_{Q-3}=0.9981$, and $P_{1-3}=0.9991$. No correlated DLCs are found in this data set. In this case the most likely hypothesis is that star 1 varies, although no clear correlated variations are seen. Hence we can say nothing about the intranight variability of this RQQSO.

1630 + 377. For this last object examined, we had good temporal coverage on May 15 and 16 and excellent coverage on 1993 May 17 in the *R* band, as illustrated in Fig. 7. On May 15 there were no significant variations. The next night the fluctuations were slightly greater, but still all insignificant, with $P_{1-2}=0.939$ the largest. During the lengthy and dense coverage on the last night, fairly high probabilities of variability were found for several of the DLCs, with $P_{Q-1}=0.980$, $P_{Q-2}=0.524$, $P_{Q-3}=0.610$, $P_{1-2}=0.99998$, $P_{1-3}>0.99999$, and $P_{2-3}=0.99999$, so those involving only the stars have very high significance, although there are no clear correlated variations. So we conclude that the most likely explanation is that at least star 3, and possibly also stars 1 or 2, varied, but we have no evidence at all that the QSO did.

4 DISCUSSION AND CONCLUSIONS

On the premise of an intrinsic origin, the intranight optical variability becomes a key observable directly related to the energy source in QSOs. Our search for optical microvariability in one radio-moderate and six radio-quiet [but all optically bright and luminous ($M_V \ll -23$)] quasi-stellar objects has yielded a highly significant detection for the radio-moderate QSO and strong hints of intranight variations of two and, possibly, three of the RQQSOs. Together with the weak evidence found for three of the five RQQSOs reported on in Paper I, we now feel fairly confident in concluding that at least some RQQSOs do fluctuate in the optical on very short time-scales. With this telescope and CCD combination, differential photometric measurements accurate to better than ~0.01 mag are possible with ~10-min integrations for sources of $m_V \approx 16$. Unfortunately, because our strongest evidence is for 0838 + 359, the only source with significant radio loudness, our results cannot as yet provide conclusive tests of the theoretical models. But we emphasize that our evidence for intranight optical variability of the RQQSO 0946 + 301 (Section 3) can also be characterized as being very substantial, since the variations span several consecutive data points, and because the light curves of the QSO, measured relative to three comparison stars present on the same CCD frame, show a distinctly correlated behaviour, both in time and amplitude. A similar pattern is observed in the case of RQQSO 1049 − 006 and, to a lesser degree, RQQSO 1206 + 459.

On the standard assumption that radio-quiet AGN lack jets that contribute significantly to their optical emission (Section 1), it becomes very likely that some of the microvariability is related to accretion disc activity. This is reasonable in that most models for AGN invoke accretion discs, and such discs are known to be subject to numerous instabilities (e.g. Rees 1984) which could be reflected in luminosity changes. The 'big blue bumps' in the spectra of many QSOs are usually attributed to the quasi-thermal emission from accretion discs, and good fits to these parts of the spectra can be obtained from standard α models (Malkan 1983; Sun & Malkan 1989), thick accretion discs (Madau 1988) and discs incorporating transonic flows and shocks (Chakrabarti & Wiita 1992). Thus UV and optical fluctuations could potentially arise from such discs. The good evidence for microvariability in the radio-quiet Seyfert 1 Akn 120 also supports the accretion disc picture (Miller & Noble 1994). A problem for the standard disc scenario is the very short time-lag between UV and optical line variabilities seen in monitoring campaigns for the Seyfert galaxies NGC 5548 and NGC 4151 (e.g. Clavel 1991; Bregman 1994). In just one case, the blazar 0716 + 714, the characteristic time-scales for optical and radio variabilities appear to change simultaneously from about a day to about a week (Quirrenbach et al. 1991). Similarly, a simultaneous radio-optical flare has been reported recently for BL Lac (Tornikoski et al. 1994). To explain such tight temporal correlations (both UV/optical and optical/radio) within the accretion disc picture would require coherent processes, most likely operating within flares in disc coronae (e.g. Lesch & Pohl 1992; Krishan & Wiita 1990, 1994). We note that these mechanisms also provide an intrinsic explanation for the ultrahigh brightness temperature measurements reported by Romero et al. (1994). A tight multiband correlation, if confirmed, would be unexpected in conventional shock-in-jet models. Jet–shock models would also be disfavoured if the level of microvariability is found to be relatively independent of the overall flaring activity in blazars, as has been observed to be the case in AO 0235 + 164 (Miller, Noble & Carini 1995, in preparation). The possibility that much of the optical and UV continuum radiation comes from optically thin free–free radiation (e.g. Barvainis 1993) should also be taken seriously; this picture predicts no time-delay between UV and optical fluctuations, but does not address the question of temporal correlations between the radio and optical bands.

As an alternative to the compact supermassive central engine, a circumnuclear starburst occurring within a dense, high-metallicity nuclear environment has been proposed as the energy source in radio-quiet quasars (Terlevich, Melnick

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& Moles 1987; Terlevich et al. 1992). In this model, most of the optical/UV and bolometric luminosity comes from young stars, whereas the compact SNRs (cSNRs) are responsible for the nuclear variability and broad spectral lines (note, however, some potential deficiencies mentioned, e.g. by Heckman 1994). Recently, Aretxaga & Terlevich (1994) have applied the model to explain, in a fairly self-consistent manner, the light curve of the extensively monitored Seyfert 1 galaxy NGC 4151, which shows sharp peaks (flares) with time-scales of some weeks, superposed on slow variations lasting a few years. Basically, under this hypothesis, the slowly varying component is related to the long-term behaviour of the cSNR, while the individual flares emitting ~ 10^{49} erg of energy are attributed to cooling instabilities in the shells of the cSNR and to SN flashes. Although such events are energetically comparable to the apparently microvariable optical component of the RQQSO 0946 + 301 reported here (~ 10^{48} erg), the ~ 10^{3} times shorter time-scales observed in the case of the RQQSO are not readily understood in this scenario.

As an immediate follow-up to this study, it now becomes extremely important to monitor bright RQQSOs more extensively, in order to determine the relative frequency of microvariability in RQQSOs. In a sample of blazars, typically a magnitude or two brighter than these radio-quiet objects, > 80 per cent evinced noticeable fluctuations when observed for periods of 8 h or longer at a stretch, while the chance of detecting microvariability in observations of under 3 h was around 35 per cent (Carini 1990). Thus the fact that the source for which we have statistically significant indications of variations is the very one that was observed for the greatest total number of hours should not be surprising. It is also necessary to examine a larger sample of RQQSOs using similarly good S/N values, in order to explore fully the characteristics of intranight optical variability associated with them. The evidence for optical microvariability reported here for both radio-quiet and radio-moderate QSOs is in accord with the recent results on long-term UV variability from the *IUE* archive, from which the *population-statistics* of the variability of radio-loud and radio-quiet QSOs are found to be practically indistinguishable (Paltani & Courvoisier 1994; also, Kinney 1991). After a much larger set of RQQSOs have been carefully examined, it should be possible to compare in detail the statistical properties of the microvariability in different classes of luminous AGN, which will have substantial implications for our understanding of the physics of their central engines.

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