Short-term optical variability of high-redshift quasi-stellar objects

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ABSTRACT

In this paper we present the results of a search for short-term variability in the optical band of selected high-luminosity, high-redshift radio-quiet quasars. Each quasar has been monitored typically for 2–4 h with a time resolution of 2–5 min and a photometric accuracy of about 0.01–0.02 mag. As a result of the significant redshift (z > 2), the covered wavelength range falls into the ultraviolet region (typically 1500–2500 Å). We have found no statistical evidence for any continuum variations larger than 0.01–0.02 mag for any of the monitored objects. Our results suggest that the presence of a short-term variability in radio-quiet quasars is unlikely even in the ultraviolet region, contrary to reports by other authors. This conclusion holds true at least for high-luminosity (large black hole mass and accretion rate?) objects. The results are consistent with the idea that significant short-term (less than 1 h) variations in active galactic nuclei, where observed, should be attributed primarily to processes in a relativistic jet.

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

1 INTRODUCTION

Optical continuum variability is one of the most distinct and definitive characteristics of quasars, revealed practically with the discovery of these objects (see Ulrich, Maraschi & Urry 1997 for a review). It has been extensively studied because of its generally unknown nature and eventually because it can be used to restrain the models of the energetic processes that may take place in quasars and produce the continuum (e.g. accretion, jet generations, etc.). Here, the shortest time-scale of the variability is of particular interest because it can impose an upper limit of the size of the emitting region. For instance, the X-ray continuum of some objects is known to vary significantly on time-scales of minutes. Many authors have also found variations in the optical band on similar time-scales but smaller amplitudes (intra-night or microvariability). For radio-loud quasars, and especially beamed ones (i.e. blazar-type objects), such an intra-night variability is indeed a well-documented feature and is due presumably to rapid processes in a relativistic jet, involving shock waves (Wagner & Witzel 1995), plasma processes (Baker et al. 1988; Krishan & Wiita 1994), etc. Interestingly, however, some authors have found such short-term variability with an amplitude of up to ~0.1 mag in radio-quiet objects, where no jet contribution to the optical continuum is expected.

Earlier microvariability observations were performed on relatively small-aperture telescopes, equipped with single-channel photomultipliers. They supposedly revealed short-term variability of about 0.1 mag in nearby Seyferts, monitored mainly in U and B bands (Lyutyi et al. 1989; Dultzin-Hacyan et al. 1992; Merkulova 2000). Unfortunately, with such equipment an adequate assessment of the photometric errors is hardly possible and, taking into account the photon noise, atmospheric instabilities, etc., the photometric errors may easily reach a value comparable to the variability amplitude claimed (see also Section 4). Petrucci et al. (1999), on the other hand, monitored a large sample of Seyfert galaxies in the I band with a CCD (i.e. a multichannel photometric device) and did not find any evidence for microvariability down to the 0.01–0.02 mag level. Similar results were reported by Gopal-Krishna, Sagar & Wiita (1995), Sagar, Gopal-Krishna & Wiita (1996), Gopal-Krishna et al. (2000), Gopal-Krishna et al. (2003, hereafter GK03), Stalin et al. (2004a) and Stalin et al. (2004b, hereafter S03), who generally did not find short-term variations above the 0.01–0.02 mag level (mainly R band) in a large sample of relatively luminous radio-quiet quasars (RQQs) among other objects. However, these authors are convinced of the reality of smaller-amplitude variations (see Section 4 for a discussion). Several other CCD-based monitoring campaigns did not present convincing evidence for short-term variations in RQQs. Rabbette et al. (1998) did not find variations above ~0.1 mag in selected higher-z RQQs. Webb & Malkan (2000) set an upper limit of the short-term variations of 0.03 mag on time-scales of an hour or so for a sample of 23 quasars (some radio-loud). Klimk, Gaskell & Hedrick (2004) found only ‘signs’ of short-term variations in a sample of narrow-line Seyfert 1 (NLS1) galaxies. Miller et al. (2000), on the other hand, presented evidence for short-term variations in an unusual NLS1 object, IRAS 13224–3809. However, the authors do not show the temporal behaviour of a similar check star, so one
cannot assess independently the real accuracy of their photometry. Similar short-term variations are reported in a nearby Seyfert 1 galaxy Akn 120 (Carini, Noble & Miller 2003), while several other similar objects showed no evidence of short-term variations.

Based on the current literature on the subject, it is concluded that, although generally a controversial issue, the short-term variability of RQQs is either very rare or non-existent; most of the higher accuracy CCD monitoring campaigns simply do not find convincing evidence for it. In spite of the lack of evidence, however, it should be pointed out that it is not entirely unexpected to find short-term variations in radio-quiet objects, particularly because the highly variable X-ray emission may also have an optical counterpart (Wiita 1996). If so, a strong wavelength dependence should be expected, in the sense that the microvariability will be much stronger at shorter wavelengths, taking into account the much higher temperature of the X-ray producing region (the central parts of an accretion disc or a hot corona above the disc). The exact wavelength dependence of the long-term variability has been debated for a long time, but the latest studies seem to confirm that the variations increase with the wavelength decrease (di Clemente et al. 1996; Cristiani et al. 1997; Giveon et al. 1999; Trevese & Vagnetti 2002; Ivezić et al. 2004). It is not known for certain whether the nature of the long-term and short-term variations is the same; therefore, it cannot be ruled out that the increase of the short-term variations toward shorter wavelengths is even greater. Based on multiwavelength monitoring of nearby Seyferts, Edelson et al. (1996) and Collier et al. (2001) confirm that the short-term variations are indeed chromatic – the far-ultraviolet (FUV) continuum varies stronger than the red continuum.

The assumption that the fast variations depend strongly on the wavelength can partially explain the apparent discrepancy in the results from earlier observations in $U$ and $B$ bands and the later observations in $R$ and $I$ bands – when no instrumental effects or improper error handling are involved in either case. An ultimate test will be a high-accuracy CCD monitoring in the UV (and FUV) region. For high-redshift quasars, this FUV region is shifted to the optical band and therefore is easily accessible from Earth. Thus, for $z \sim 2$ the $R$-band monitoring covers the region of 2000–2500 Å in the quasar’s rest frame, and is practically a FUV monitoring.

In this paper we present the results of such a monitoring of 18 high-redshift, high-luminosity RQQs with an average redshift of 2.5 and a typical visual magnitude of 16.5. Our goal is to clarify the role of the wavelength in the short-term variability as well as to fill the high-luminosity, high-redshift end in the distribution of quasi-stellar objects (QSOs), having been subjects of short-term variability monitoring campaigns so far.

2 OBSERVATIONAL DATA
The observed objects (Table 1) were selected from the latest catalogue (Véron-Cetty & Véron 2003, hereafter VCV03), and are shown in Table 1. Column 1 displays the most common name of the object (taken from VCV03). The redshift is shown in column 2. Columns 3, 4 and 5 display $V$, $R_C$, and $I_C$ magnitudes of the quasars, which are either taken from the literature or based on our measurements, accurate to $\sim 0.1$ mag. The absolute $V$-band magnitude ($M_V$) is calculated based on $V$ from column 3 ($q_0 = 0$ and $H = 50$ km s$^{-1}$ Mpc$^{-1}$) are adopted, as in VCV03), and is shown in column 6. The last column (column 7) indicates the source for the magnitudes in columns 3, 4 and 5; NED denotes the NASA/IPAC Extragalactic Database, VCV denotes VCV03 and t.w. denotes this work.

### Table 1. Objects.

| Object name | $z$ | $V$ | $R_C$ | $I_C$ | $M_V$ | Reference |
|-------------|-----|-----|-------|-------|-------|-----------|
| Q 0013+0213 | 1.55 | 16.4 |       |       | −29.0 | NED |
| S5 0014+81  | 3.39 | 16.5 |       |       | −31.1 | NED |
| PHL 957     | 2.69 | 16.6 |       |       | −30.3 | VCV |
| UM 673      | 2.72 | 17.0 | 16.8  |       | −29.9 | NED |
| Q 0226−1024 | 2.27 | 16.3 | 15.5  | 14.6  | −30.1 | t.w. |
| HS 0741+4741| 3.20 | 16.4 | 16.2  | 16.1  | −31.0 | t.w. |
| PG 1247+268 | 2.04 | 15.6 |       |       | −30.5 | VCV |
| HS 1312+7837| 2.00 | 15.8 |       |       | −30.2 | VCV |
| SBS 1425+606| 3.16 | 15.8 |       |       | −31.5 | VCV |
| SBS 1542+541| 2.37 | 17.1 | 16.9  |       | −29.4 | t.w. |
| HS 1603+3820 | 2.51 | 16.2 | 15.9  |       | −30.5 | t.w. |
| HS 1626+6433 | 2.32 | 16.5 | 16.3  |       | −30.0 | t.w. |
| HS 1700+6416 | 2.74 | 16.1 | 15.7  |       | −30.9 | t.w. |
| SBSS 1711+579| 3.00 | 18.0 |       |       | −29.2 | NED |
| HS 1946+7658 | 3.05 | 16.2 | 15.8  |       | −31.5 | NED |
| HS 2103+1843 | 2.21 | 16.8 |       |       | −29.5 | VCV |
| HS 2140+2403 | 2.17 | 17.8 |       |       | −28.5 | VCV |
| HS 2337+1845 | 2.62 | 16.9 | 16.7  |       | −29.9 | NED |

2.1 Object selection
The objects were selected upon several criteria (see below). Despite our best intentions, a few objects do not satisfy one or another formal condition, although we include the results of their monitoring because they do not alter our main conclusions.

(i) Radio quietness. All the objects were required to be radio-quiet or to have undetected radio emission, which at least suggests that they are not significantly radio-loud in terms of the Kellermann index ($R_K = L_{Radio}/L_{Opt}$; Kellermann et al. 1989). This is the most important requirement because we want to isolate the short-term variability due to a jet from the one that could possibly be associated with an accretion disc. The only exception is S5 0014+81, which has $R_K \approx 250$ and technically should be considered radio-loud. Any possible detection of microvariations of this object should be interpreted with care.

(ii) Photometric errors $\sigma \approx 0.01–0.02$ mag and a time resolution of the light curves of 5 min or better. This requirement is important for a successful time and amplitude resolution of the microvariations as they are expected to occur in active galactic nuclei (AGNs). It naturally means visually bright objects. To satisfy this requirement by improving the signal-to-noise ratio of the photometry, some objects had to be observed with no photometric filter applied (see Section 2.2). Still, due to the unexpected weakness of some objects or non-excellent atmospheric conditions, this condition could not be entirely satisfied for some objects (Table 2).

(iii) High redshift: $z > 2$. This requirement is imposed in order to ensure that the FUV region is observed, even in cases where no filter is used (see below). Thus, the covered rest-frame wavelength region falls generally into the 1000–3000 Å range (Table 2). This requirement was fulfilled for all the objects, except for Q 0013+0213 ($z = 1.55$).

(iv) Convenient comparison stars in the field. We required at least one bright star (main standard) to be in the field of the quasar and at least one more check star of moderate brightness, which is essential for a reliable differential photometry. This requirement was easily satisfied for all QSOs we initially intended to observe.
Several tens of quasars from VCV03 satisfy the requirements above. We naturally had to exclude objects with a declination $\delta < -15^\circ$ (see the next section).

### 2.2 Observations and photometry

The observations were performed with the 0.6-m reflector of the Belogradchik Observatory, Bulgaria, equipped with a CCD SBIG ST-8 camera (Bachev, Strigachev & Petrov 1999), the 2.0-m Rozhen National Observatory, Bulgaria, equipped with a Photometrix AT200 CCD, the 0.5-m Skinakas Observatory, Crete, where a Photometrix CH360 camera was used. The telescopes were equipped with standard $BVR_C$ filters. All observations were performed on presumably clear, photometric nights. In order to diminish any possible atmospheric effects, the objects were preferably monitored during culmination, where the airmass does not change much for the time of the monitoring. This also ensured a relatively good seeing, typically 1.5–2.5 arcsec.

Table 2 presents the observations. Each object was observed once (column 2) with the instrument shown in column 3. Column 4 shows the rest-frame region fall into typical sensitivity of the camera in use there roughly mimics the transition of the high redshift the total monitoring time is much shorter in the rest frame of the quasars – the rest-frame monitoring time is given in column 9 and is typically of about an hour or so. The frame exposure time (in seconds) and the total number of exposures are given in columns 8 and 9.

| Object name | Date          | Instrument | Filter | $\lambda_{\text{Rest}}$ | $T_{\text{Tot}}$ | $T_{\text{Exp}}$ | $N$ | Aperture | $\sigma$ | $\Delta m$ | $P$ (per cent) |
|-------------|---------------|------------|--------|-------------------------|-----------------|-----------------|----|----------|---------|-----------|----------------|
| X 0013+0213 | 2003/08/28    | 0.6 AOB    | $R$    | 1770–3730               | 2.8             | 1.1             | 150 | 61       | 0.018   | 0.018     | 0              |
| S 0014+081  | 1999/11/03    | 0.6 AOB    | $R$    | 1030–2160               | 4.4             | 1.0             | 180 | 47       | 0.015   | 0.019     | 50             |
| PHL 957     | 2002/09/20    | 1.3 SkO    | $R$    | 1520–2090               | 1.8             | 0.5             | 300 | 20       | 0.015   | 0.022     | 81             |
| UM 673      | 2003/09/04    | 1.3 SkO    | $R$    | 1500–2070               | 2.7             | 0.7             | 300 | 29       | 0.006   | 0.007     | 31             |
| Q 0226–1024 | 2003/12/17    | 0.6 AOB    | $R$    | 1380–2900               | 3.4             | 1.0             | 120 | 61       | 0.012   | 0.013     | 3              |
| HS 0741+4741| 2003/12/17    | 0.6 AOB    | $R$    | 1070–2260               | 2.6             | 0.7             | 120 | 65       | 0.023   | 0.022     | 0              |
| PG 1247+268 | 2004/03/21    | 2.0 NAO    | $R$    | 1840–2530               | 4.9             | 1.6             | 300 | 47       | 0.003   | 0.002     | 91             |
| HS 1312+7837| 2004/05/13    | 0.5 NAO    | $R$    | 1500–3170               | 3.9             | 1.3             | 300 | 28       | 0.037   | 0.034     | 13             |
| SBS 1425+606| 2004/05/12    | 0.5 NAO    | $R$    | 1080–2280               | 3.9             | 0.9             | 300 | 40       | 0.056   | 0.047     | 23             |
| SBS 1542+541| 2006/06/01    | 0.6 AOB    | $R$    | 1340–2820               | 2.8             | 0.8             | 180 | 49       | 0.028   | 0.027     | 0              |
| HS 1603+3820| 2006/06/03    | 0.6 AOB    | $R$    | 1280–2700               | 3.3             | 0.9             | 180 | 56       | 0.014   | 0.013     | 0              |
| HS 1626+6343| 2003/05/31    | 0.6 AOB    | $R$    | 1350–2860               | 3.2             | 1.0             | 180 | 60       | 0.018   | 0.018     | 0              |
| HS 1700+6416| 2003/05/30    | 0.6 AOB    | $R$    | 1200–2540               | 3.8             | 1.0             | 180 | 59       | 0.013   | 0.016     | 28             |
| SBS 1711+579| 2002/06/16    | 0.6 AOB    | $R$    | 1130–2380               | 3.1             | 0.8             | 120 | 73       | 0.032   | 0.037     | 9              |
| HS 1946+7658| 2002/09/17    | 1.3 SkO    | $R$    | 1380–1900               | 3.1             | 0.8             | 180 | 7        | 0.003   | 0.002     | 5              |
| HS 2103+1843| 2002/09/17    | 1.3 SkO    | $R$    | 1750–2400               | 1.4             | 0.4             | 300 | 16       | 0.009   | 0.010     | 39             |
| HS 2140+2403| 2003/08/12    | 1.3 SkO    | $R$    | 1770–2430               | 4.2             | 1.3             | 300 | 45       | 0.012   | 0.017     | 85             |
| HS 2337+1845| 2002/09/16    | 1.3 SkO    | $R$    | 1550–2130               | 3.8             | 1.0             | 300 | 31       | 0.011   | 0.015     | 58             |

### 3 RESULTS

Figs 1–3 show the results of our short-term variability search. The top panel of each box displays the magnitude difference between the quasar of interest and the main standard; the bottom panel shows the difference between a check star and the main standard. The check star was chosen on a basis of spatial and magnitude proximity to the quasar. We preferred to use check stars of similar magnitude as the monitored object, because this is the best way to account for the real photometric errors of an object of such magnitude. As many authors pointed out, the formal (theoretical) errors that the program codes return are usually smaller than the real errors by a factor of typically 1.5–1.75 (see S03, and references within). Our analysis indicates, on average, $\sigma_{\text{Real}}/\sigma_{\text{Form}} \simeq 1.3$. This implies that the errors indicated...
Short-term variability of QSOs

Figure 1. Results from the short-term variability search. The upper panel of each box shows the magnitude difference \((m_{QSO} - m_{S1})\) (filled symbols), and the lower panel shows \((m_{S2} - m_{S1})\) (open symbols). \(S1\) is the main standard and \(S2\) is a check star of a magnitude as close as possible to the magnitude of the quasar (see text). Theoretical (see Section 3) photometric errors at the 1\(\sigma\) level are indicated as error bars. The name of each monitored object and the date of observations are shown at the top of each box. The abcissa represents UT in h (i.e. one abcissa subdivision corresponds to 10 min). Each upper panel has the same vertical scalefactor as the corresponding lower panel, but the value may differ from object to object.

Figure 2. See Fig. 1.

This behaviour is consistent with the idea that the real photometric errors approach the theoretical when the photon noise is the primary error source and approach some minimum greater than zero when it is not. This minimum turns out to be of the order of 0.005–0.01 mag and should be considered as the accuracy limit of our differential photometry (Section 4.2).

Table 2 (column 12) shows the standard deviation \((\Delta m)\) of the \((QSO - S1)\) light curve for the monitored period. For most of the objects, this \(\Delta m\) is statistically indistinguishable even from the theoretical photometric error (column 11). Column 13 shows the results of a \(\chi^2\) analysis, assuming that \(\sigma = \sigma_{\text{Real}} = 1.3\sigma_{\text{Form}}\), i.e. it gives the probability of ruling out the null hypothesis of non-variability. It is seen that from a statistical point of view, none of the objects monitored shows variability above the 95 per cent confidence level. In other words, the main result of our work indicates no presence of short-term variability in any of the monitoring objects.

4 DISCUSSION

4.1 High-\(z\) caveats

Monitoring high-redshift objects has the advantage that the FUV region is shifted to the optical band, and therefore is directly accessible to the ground observations. Furthermore, there is no need of a broad-band filter to restrict the wavelength region covered, as far as the entire UV continuum is assumed to be emitted by a relatively small region – the inner portion of an accretion disc. As a disadvantage of the high \(z\) can be mentioned the corresponding contraction of the total monitoring time in the QSO rest frame (Table 2), which makes a monitoring of few hours probably not enough to reveal a possible variability (Section 4.3). For very high-\(z\) objects \((z > 4)\) the Lyman forests fall into the visual range; therefore, such objects should better be monitored in the infrared.
When monitoring the UV continuum, it is necessary to take into account that possible strong emission lines fall into the observed region, such as Lyα, C IV λ1549, Fe II multiplets, etc. The line-emitting region is located further out from the central parts of an accretion disc and is not expected to be variable over intra-night time-scales. Therefore, the presence of such lines may lead to the underestimation of the deducted continuum variability amplitude (or the upper limit of such), and appropriate correction may be in order. This effect in principle is present in any spectral region, but is especially strong in the UV; the equivalent width of the lines there can easily exceed 300–400 Å, which means that the lines can contribute with up to 50 per cent to the total flux from the region.

A sample of high-redshift quasars, due to the selection effects, by all means implies a sample of very luminous quasars (Table 1). Statistically, the highest luminosity, presumably not beamed quasars in the Universe, even if their luminosity is somewhat amplified by macrolensing, would most probably be powered by black holes of extremely large mass ($M_{BH} \sim 10^{9}$–$10^{10} M_\odot$) fed at about the Eddington limit. Possible implications are discussed in Section 4.3.

### 4.2 Photometric errors

The proof of the existence of any short-term variations, especially small-scale ones, depends critically on the correct assessment of the photometric errors. Because the atmosphere acts like a colour filter of variable transparency, the differential photometry of two stars of different colours should be affected by the airmass changes during the monitoring. The practice of not using a filter during the monitoring seems to be especially prone to atmospheric effects (Section 2). As S03 pointed out, however, the effect of the colours of the comparison stars on the differential light curve is negligible for a specific band (see also Carini et al. 1992). Because the cameras we used (Section 2) are basically sensitive in $V$, $R$ and $I$ bands, not using a filter means that we add the signal in these three bands together; if any colour effect is negligible for an individual filter this should hold true for the sum as well. The effect ought to be explored carefully should the camera be highly sensitive in $U$ and $B$ bands, where extinction coefficients in reduction equations are the largest (see S03 for details). In any case, should we observe any trends in the differential light curves, we would search for any magnitude–airmass correlation; this should be done any time when trends are observed independently, whether a filter is used or not (e.g. Klimek et al. 2004).

Our analysis of the $\sigma_{\text{real}}/\sigma_{\text{form}}$ ratio suggests the presence of a minimal error of the photometry (see Section 3), which for our observations is estimated to be $\sim 0.005$ mag, but probably may vary. The presence of a minimal error may or may not be the case of other researchers’ photometry; in any case, such a possibility should be carefully explored. It is understandable that if this is really the case, by adjusting the individual $\sigma_{\text{form}}$ by the average $\langle \sigma_{\text{real}}/\sigma_{\text{form}} \rangle$, we underestimate the errors of some objects but underestimate others, which may lead to a wrong conclusion about the variability properties of the latter. In any case, having check stars of a magnitude close to that of the quasar seems to be the correct way to account for any spurious sources of errors.

One can think of many possibilities leading to an upper limit of the photometric accuracy: non-perfect flat-field correction, parasite light and optics imperfections are among them. It is not that important to know the sources of all errors; what is actually important is to be aware of their magnitude.

### 4.3 Comparison with other results

Because some researchers find clear indications of short-term variability in radio-quiet objects, an immediate question would be why our results do not reveal such. There are several possibilities, related to the following.

#### 4.3.1 Quasar parameters

By short-term variability, intra-night variability is often assumed. However, the objects observed may be very different, i.e. variations that are well seen over a night in a low-mass NLS1 nucleus might require much longer time to be detected in a powerful quasar. In fact, most of the monitoring campaigns do not distinguish between quasars with different accretion parameters (e.g. black hole mass, accretion rate, etc.). As we have mentioned above, our objects would probably have very large black hole masses, which may result in larger variability times. If the UV-continuum variations occur at a fixed distance (in Schwarzschild radii) from the black hole and reprocessing of hard radiation is primarily responsible for them, the variability time-scale will scale linearly with the mass (see also Section 4.4). The time contraction (due to the high redshift) additionally worsens the situation in our case.

Because the time-scale of the variability is related to the variability amplitude (through the structure function; di Clemente et al. 1996), not enough time coverage may equally mean not good enough photometric accuracy as a possible explanation of non-detection of the variability. Indeed, it is often assumed that the long-term variability amplitude anticorrelates with the luminosity (Cristiani et al. 1997; Paltani & Courvoisier 1997). However, the exact relation between the variability and luminosity is a subject of discussion. Furthermore, it may or may not be the same for the short-term variations.

#### 4.3.2 Interpretation of variability results

When we compare our results with results from other studies, where short-term variations in RQQs are sometimes reported, we see that often these studies have better accuracy and time coverage than our study. It is obvious that this may be one of the reasons why we did not detect any variations in our QSO sample. However, one should be somewhat sceptical when photometry of extremely high accuracy is reported. We have already mentioned that our analysis suggests the presence of an upper limit of the photometric accuracy (Section 4.2). This effect ought to be explored carefully. The role of possible instrumental effects, which in general may be difficult to account for, should also not be underestimated. Klimek et al. (2004), for instance, give a good example of how spurious effects, related to seeing, position of the star on the chip, etc., can affect the measured magnitudes. The exposure time can also affect the $\sigma_{\text{real}}/\sigma_{\text{form}}$ ratio by the number of cosmic rays, for instance (these can hardly be fully removed). One indication of a possible underestimation of the real errors of the photometry is finding many ‘variable’ comparison stars in quasar fields. It is statistically improbable that a significant number of random stars will turn out to be variable on time-scales of an hour or so. Such comparison star variations are indeed reported in studies, where the quasar of interest is also sometimes found to vary similarly (Gopal-Krishna et al. 1995; Sagar et al. 1996; Gopal-Krishna et al. 2000; GK03; S03). In any case, for those objects, for which evidence for short-term variability is presented, an independent confirmation is by all means required.

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Webelieve that any variability amplitude calculations should be true especially when the variations are very small or negligible. Different approaches that may lead to different conclusions on the UV flares is fixed to a simple model. If the size of an active region producing short-term events of number...the variable hard X-ray emission originates in the centre, then...the central mass in $10^8 M_{\odot}$...the shortest variability time-scale ($\tau_{\text{var}}$) proves undoubtedly the reality of the variations (by ruling out the non-variability hypothesis at significant level). We follow such an approach in this paper.

4.4 Implications for variability models

A non-detection of variations over a certain time-scale in a class of objects is not necessarily a negative result, because it still provides some constraints on the physical models of the central engine. It is understandable that if some thermal mechanism is responsible for the continuum changes at certain wavelength $\lambda$ (FUV in our case), these changes should mostly occur in the regions where the emission of such $\lambda_{\text{UV}}$ is primarily coming from, (i.e. regions having the corresponding high enough temperature). This is so, because a temperature change affects to a greater extend the Rayleigh–Jeans part of the Planck curve, rather than the Wien part; that is, the continuum around $\lambda_{\text{UV}}$ will be effectively enhanced only if already $T_{\text{UV}}(r) \gtrsim (hc/k_B\lambda_{\text{UV}})$. Because we here consider basically one spectral region, we can use the expression for the radial dependence of the temperature, assuming a standard Shakura–Sunyaev disc, $T_{\text{Edd}}(r) \propto m^{1/4} M_{\text{BH}}^{8/3} r^{-3/4}$ (e.g. Frank, King & Raine 2002), to find the dependence of the radius of a fixed temperature on the accretion parameters: $r_{\text{UV}} \propto m^{1/5} M_{\text{BH}}^{3/5}$. Here, $m$ is the accretion rate (in Eddington units), $M_{\text{BH}}$ is the black hole mass and $r$ is the radius in linear units. Thus, $r_{\text{UV}}$ will be the radial distance of the region, primarily responsible for the UV-continuum changes; further out the temperature is too low, and inward the area decreases (and respectively the total flux).

The shortest variability time-scale ($\tau_{\text{var}}$) is usually associated with the light-crossing time and implies reprocessing of hard (X-ray) radiation into the UV–optical region (Ulrich et al. 1997). If the variable hard X-ray emission originates in the centre, then $\tau_{\text{var}} \simeq 0.25 M_{\odot}(r_{\text{UV}}/R_{\odot})$ or $\tau_{\text{var}} \propto r_{\text{UV}} \propto m^{1/5} M_{\text{BH}}^{-3/5}$. Here, $M_{\odot}$ is the central mass in $10^8 M_{\odot}$ and $R_{\odot}$ is the Schwarzschid radius. One sees therefore (Section 4.3) that this time may not be enough to reveal any intra-night variations in a powerful quasar ($M_{\text{BH}} \simeq 10^{8-10} M_{\odot}$). On the other hand, the variable hard radiation may not necessarily come from the centre, but from a hot corona above the disc instead (Merloni & Fabian 2001). The resulting $\tau_{\text{var}}$ in such a case can be much shorter. One can explore roughly the amplitude dependence on the accretion parameter based on a very simple model. If the size of an active region producing short-term UV flares is fixed to $l$, the variability amplitude (assuming random flare-producing events of number $N$ above a flat reprocessor – accretion disc) should be estimated as $N^{-1/2} \propto 1/l$ or respectively $\propto m^{-1/3} M_{\text{BH}}^{-2/3}$. This relation, for an Eddington-limited accretion, gives ~100 times smaller amplitude of the microvariations for a powerful quasar, compared to a NLS1 galaxy with $M_{\text{BH}} \simeq 10^8 M_{\odot}$. In both cases we see that it is far more likely to observe short-term variations in AGNs of lower central mass (e.g. NLS1, mini-Seyferts).

If the accretion operates through an optically thick advective disc (i.e. slim disc; Abramowicz et al. 1988), the radial temperature scales as $T_{\text{Edd}}(r) \propto M_{\text{BH}}^{8/5} r^{-1/2}$ (Watarai & Fukue 1999). Similar analysis will reveal in such a case that the amplitude of the variations scales as $M_{\text{BH}}^{-1/2}$.

Another possible explanation of the variations is based on the instabilities of the flow itself, rather than on reprocessing. If we assume that the inner part of the flow operates through an optically thin advective mode [the advection-dominated accretion flow (ADAF); Narayan, Mahadevan & Quataert 1998], the border between the ADAF and the outer thin disc may be a good candidate for the region where these instabilities occur (Gracia et al. 2003; Krishan, Ramadurai & Wiita 2003). Again, FUV variations will be effectively generated if this transition happens to occur close to $r_{\text{UV}}$ (see above). The time-scale of such changes may be associated with the accretion time-scale of the ADAF (close to the free-fall time-scale), which is about $\tau_{\text{var}} \simeq 0.4 M_{\odot}(r/R_{\odot})^{3/2}$ and may be as small as few hours in the case of very small ADAF section. The thin disc–ADAF transition depends on the accretion parameters and is supposed occur at about the last stable orbit if the accretion rate is relatively high, $\dot{m} \gtrsim 0.1$ (Różańska & Czerny 2000). Yet, for a very massive and powerful quasar, such a mechanism does not seem to be able to generate significant short-term variations.

If any variations are detected, the variability pattern (the structure function) will possibly be able to distinguish between explosive events and instabilities at the ADAF–thin disc border.

5 CONCLUSIONS AND SUMMARY

In this paper we have presented results from a short-term variability monitoring of luminous high-redshift radio-quiet QSOs. The FUV (rest frame) continuum has been observed for several hours (about an hour in the rest frame). No statistical evidence for variations above the 0.01–0.02 mag level has been found in any of the observed objects. We conclude that such variations, if they exist at all, are untypical at least for these objects. On the other hand, it is completely possible that our photometric accuracy and time coverage may simply not be enough to reveal possible variations at the microlevel, because such are sometimes reported in other studies. However, we stress the importance of the correct assessment of the photometric errors for the interpretation of the variability results, suggesting that in some of these studies the errors may have been underestimated.

In spite of the fact that we failed to detect any short-term variations in a large sample of quasars, our analysis suggests that these may be well detectable in some objects with smaller black hole masses (e.g. NLS1s or mini-Seyferts). This possibility is supported by the fact that direct (space) observations of the UV continuum indeed reveal day-scale variations in some objects. Based on our experience and taking into account the results of other researchers, we can propose several possible further steps that can be successfully performed with small telescopes, and can contribute significantly to the understanding of the nature of the short-term variability in QSOs.

(i) Observations of high-redshift luminous QSOs on time-scales of days or weeks in order to reveal the shortest variability time-scale of these powerful objects.

(ii) Observations of a selected lower-redshift NLS1 to clarify the role of the mass and accretion rate on the variability time-scales in the optical band and the near-UV.
(iii) Once the variations are clearly detected, finding the structure function eventually in different colours will be of extreme importance for a successful modelling of the variability.

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