Rapid optical variability in radio-quiet QSOs

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ABSTRACT

We report results of the observations at the Vainu Bappu Observatory and the Uttar Pradesh State Observatory of eight radio-quiet quasi-stellar objects (RQQSOs) during 1996-99. This is a part of our ongoing programme to search for intranight optical variability in RQQSOs. Additional evidence for very rapid variability in three of the five optically bright and very luminous RQQSOs we had observed earlier, 1049−006, 1444+408 and 1630+377, was found. Of the three newly observed RQQSOs, the data for 0043+039 were too noisy to allow conclusions about variability to be drawn, but 0748+294 and 0824+098 show strong hints of microvariability. We also present a summary of the results from our entire programme to date, which includes observations of 16 radio-quiet and one radio weak QSO, and compare the general properties of rapid variability in radio quiet versus radio loud AGN as determined from our work and that of several other groups. Observations of this kind are likely to play a key role in understanding the relative contributions of accretion disks and relativistic plasma jets to rapid optical fluctuations of AGN.

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1. Introduction

The generation of significant amounts of synchrotron emission in radio quiet quasars (RQQSOs) is currently a much debated issue. Whereas a number of arguments against the presence of relativistic non-thermal jets in RQQSOs have been advanced (Antonucci, Barvainis & Alloin 1990; Sopp & Alexander 1991; Stein 1996), some evidence for faint radio jets in at least a fraction of RQQSOs has emerged from deep VLA imaging programmes and related studies (Miller, Rawlings & Saunders 1993; Kellermann et al. 1994; Falcke, Sherwood & Patnaik 1996; Falcke, Patnaik & Sherwood 1996). Very recently, VLBA studies of a group of 12 radio-quiet and radio-intermediate (cf. Miller et al. 1993) quasars have also indicated the presence of weak jets in 8 of them (Blundell & Beasley 1998).

Intranight optical flux variations have been well established in the case of optically violent variable quasars and BL Lacertae objects which are believed to eject relativistic jets (e.g., Miller, Carini & Goodrich 1989; Carini et al. 1991, 1992; Carini & Miller 1992; Heidt & Wagner 1996, 1998; Noble 1997). Miller and collaborators have called the briefer (on timescales of seconds to a few hours) and usually relatively small (typically $\sim$0.03 mag) variations, microvariability (e.g., Miller & Noble 1996). As this nomenclature has been adopted by many other groups (e.g., de Diego et al. 1998; Petrucci et al. 1999; Romero et al. 1999) we shall typically use the terms intraday (or intranight) variability and microvariability interchangeably; if a distinction is to be made, then observations with temporal resolution of substantially less than one hour can measure microvariability, while coarser sampling could reveal only intraday fluctuations.

Shocks propagating down relativistic jets certainly provide a plausible explanation for the frequent occurrence of rapid fluctuations in both the radio and optical intensities of blazars (e.g., Marscher, Gear & Travis 1992; Gopal-Krishna & Wiita 1992; Camenzind & Krockenberger 1992; for a review see Wagner & Witzel 1995). Nonetheless, other mechanisms may also play a significant role in causing such fluctuations, especially in the case of RQQSOs, where any contribution from the jet, if at all present, must be very weak. Most viable alternatives invoke instabilities in the accretion disks, or in the coronae that may be associated with them (for a review, see Wiita 1996).

Unambiguous detection of intranight variability in bona-fide RQQSOs can thus provide important clues to the alternative physical mechanisms that may be occurring on the smallest scales in these powerful AGN (Gopal-Krishna, Wiita & Altieri 1993, hereafter GKWA; Gopal-Krishna, Sagar & Wiita 1993a). Recent observations suggest that intranight optical variability, which is fairly common among flat spectrum radio-loud quasars, is rarer among radio weak AGN (Jang & Miller 1995; 1997); however, high luminosity QSOs were not covered in that programme. To keep a focus on genuine RQQSOs, we initiated a search for intranight optical variations in the QSOs which are apparently bright (V $\sim$ 16 mag), highly luminous ($M_V \leq -25$ mag), and practically radio silent ($R \ll 1$, where R is the ratio of radio [5 GHz] to optical [440 nm] flux densities in the rest-frame), (Gopal-Krishna, Sagar & Wiita 1993b, hereafter Paper I; 1995, Paper II; Sagar, Gopal-Krishna & Wiita 1996, Paper III). The sensitivity and sampling rate of these observations have reached the point where rapid fluctuations of a few per cent occurring in a few minutes can be convincingly detected, using the CCD chip as an N-star photometer. A special emphasis in our programme is to achieve a dense sampling of the light curve (minimum 5-10 data points per hour) for as many QSOs as possible, so that the existence of micro-variability among RQQSOs can be ascertained.

In Papers I, II and III, we have reported the monitoring of 13 RQQSOs ($R \ll 1$), and one essentially radio quiet QSO, 0838+359, with $R = 5$; $R < 10$ is generally considered to distinguish radio quiet from radio loud objects (Kellermann et al. 1989). These observations were made using the 2.34 metre Vainu Bappu Telescope (VBT). Our data clearly revealed microvariability for at least one RQQSO, namely, 0946+301, and for the radio weak QSO 0838+359. Intranight variability was possibly seen for several other RQQSOs, including 0117+213, 1049−006, 1444+408 and 1630+377. In this paper (Paper IV), we report new observations carried out during 1996–1999 which cover eight RQQSOs (including three newly added to our sample, 0043+039, 0748+294 and 0824+098). We also present a summary of all the observations completed thus far under this programme and a discussion of the differences between the types of rapid variability seen in radio quiet and radio loud quasars based upon our work and that of several other groups who have recently addressed this question.

2. Observations and data reduction

The RQQSOs for the present programme were selected from the lists of Hewitt & Burbidge (1993) and Véron-Cetty & Véron (1993), following the criteria outlined in Paper II. These criteria ensure that the selected objects are bona-fide optically luminous QSOs, with extremely weak radio emission (flux density < 1 mJy at 6 cm, Kellermann et al. 1994; 0838+359 was later found to have a ∼6 mJy nuclear source, Paper II); and are apparently bright enough ($V \approx 16$ mag) to yield a signal-to-noise ratio of ∼100 within ≤ 10 minutes of exposure time. Another requirement was the presence of at least three suitable comparison stars on the CCD frame containing the RQQSO. Taking a clue from the blazars, for which it has been shown that the probability of observing intranight variability is greatly enhanced by monitoring the object for at least 3 to 4 hours continuously (Carini 1990; Noble 1995), we have attempted to follow each RQQSO for a minimum of 4 hours, preferably close to the meridian transit.

Basic information about the eight RQQSOs and the dates of the observations analysed herein are provided in Table 1. A Hubble constant $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ are assumed for computing M_V.

About half of the new observations reported here were carried out with the 2.34 meter Vainu Bappu Telescope (VBT) of the Indian Institute of Astrophysics. The detector used was a cryogenically cooled Tektronix (TK 1024AB2) CCD chip mounted at the $f/3.23$ prime focus of the VBT. The chip is front illuminated and metachrome coated for enhanced UV response. This chip has 1024 × 1024 pixels of $\sim$ 24 microns square, with each pixel dimension corresponding to $\sim$ 0.63 arcsec on the sky, so that the total area covered by a CCD frame is 10.75 × 10.75 arcmin^2. The read out noise was 4.00 electrons and the gain was 4.00 electrons/ADU (Subramaniam 1996). Typical seeing was around 2 arcsec, adequate to provide accurate relative magnitudes for point-like objects. Further details of the observing procedure currently used are given in Paper II.

The VBT observations were supplemented by data obtained at the 1.04 m Sampuranand reflector of the Uttar Pradesh State Observatory (UPSO) at Naini Tal. This differential photometry also used a 1024 × 1024 Tektronix CCD system, this time at the $f/13$ Cassegrain focus. In order to improve the S/N ratio, the observations were taken in a binning mode of 2 × 2 pixels. Each super pixel then corresponds to 0.7 arcsec in each dimension and the entire chip covers a field of 6.0 × 6.0 arcmin^2 (Durgapal, Pandey, & Mohan 1997). Read out noise was 7 electrons and the gain was 11.98 electrons/ADU. Typical seeing was around 1.5 arcsec.

The procedure for data reduction, including the differential photometry using the DAOPHOT software package, has been described in Paper II, together with the details of photometric error estimation. We reduce the data using 5, 7, and 10 pixel radii; in general the best SNR is obtained for 7 pixel radii, and figures based on those reductions are displayed. In general, the data reduced with different apertures were found to be in excellent agreement, the only exception thus far being a single data point for the RQQSO 0748+294, which is discussed explicitly below. Whenever we note correlated trends on all the differential light curves (DLCs) involving a QSO we carefully visually examine all frames of that session individually; with the exception of the single data point for 0748+294, we did not find anything anomalous in our data.

The position offsets of the comparison stars we used from the respective QSOs are given in Table 2. For each frame three or four comparison stars were reduced in a manner identical to that for the QSO. It may be further noted that in general, for QSOs common to Papers II and/or III, the comparison stars have been designated as in those previous papers; also, for the objects for which repeated observations have been made, the V−R colours for the QSOs and their comparison stars were sufficiently close that no difficulties should be induced in performing these comparisons (cf. Papers I and II).

3. Differential light curves (DLCs)

Plots of differential magnitudes versus time for seven of the eight RQQSOs are shown in Figures 1–7. As discussed in Paper II, the statistical errors as given from the DAOPHOT software seem to be too small by a factor of about 1.75, and we have made a correction for this in our formal analysis of variability. Also, we continue to use the conservative statistical criterion of Kestevan, 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; these tests are applied to the entire datatrain in an observing run. In some cases a few obviously poor quality data points yield nominally significant variations by this criterion. We do not take such situations to be compelling evidence for variability, and carefully examine each frame used in the analysis that appears to provide evidence for variations; we discard any suspicious points (cosmic ray hits; variations in CCD response, etc.) before performing the statistical analysis. Furthermore, only if we see correlated variations (both in time and amplitude) on the different DLCs involving a given object with no problems seen on the frame, or if the statistical criterion depends upon a chain of points showing variations would we claim that the source exhibits microvariability. We now discuss the results for each of the eight RQQSOs.

0043+039. This RQQSO was newly included in our programme. The data taken on 1996 December 20 were of very poor quality, and those for 1996 December 21, while slightly better, were still much noisier than usual, with a signal-to-noise ratio (SNR) of ~ 40 during the ~ 3 hours of monitoring. Therefore, we do not display these data, and merely note that there is no strong formal indication of variance for the QSO, except with respect to star 3. Quantitatively, for the DLCs derived from the second night's observations, $P_{Q-1} = 0.8506, P_{Q-2} = 0.5388$, and $P_{Q-3} > 0.999999$, while $P_{1-2} = 0.0195, P_{1-3} = 0.2525$, and $P_{2-3} = 0.0188$, so there is merely a possibility that the QSO is variable, in that the statistical indications are greater for it than for any star. Additional monitoring of this QSO under better conditions would be desirable.

0748+294. This RQQSO was also newly included in our programme and monitored with our typically high SNR > 100, for 7 hours on 1999 February 14. The DLCs for this night are displayed in Fig. 1a, using our default photometric aperture of 7 pixel radius. Near the start of observations a conspicuous bump with a peak deflection of ~ 0.08 mag is seen in all the three DLCs of the QSO, but not on any of the DLCs involving only the comparison stars. In addition to this two-data point fluctuation, a single-point fluctuation (spike) of ~ 0.05 mag is seen at UT 18.3. As usual, in order to ascertain the significance of these features we generated DLCs using photometric apertures of 5 and 10 pixel radii. The only significant difference found between the sets of DLCs using 5, 7 and 10 pixel radii is that the 5-pixel reductions show the bump found in the other two reductions at UT 14.0 to be a single-point fluctuation (instead of a 2-point bump). In all of our data obtained so far in this programme this is the only instance where such an inconsistency has occurred. Since the origin of this difference is not understood (although we note that the discrepant point on the DLCs is very close to the beginning of the monitoring, when the high airmass may have caused some small but significant and highly abnormal deformation of the image), we prefer to treat this bump as being no more significant than a single point spike, as seen in Fig. 1b, which was generated using the 5-pixel radius aperture. Of course such single-point excursions cannot be wholly convincing, and we therefore do not make an absolute claim that microvariability has been detected in this case (or the others of this type). While we have performed extremely careful frame-by-frame analyses so that typical cosmic ray (CR) hits or transient CCD defects have been rejected as possible explanations, it is not impossible that an abnormally compact CR hit could be responsible for such an apparent flare.

In performing a formal statistical analysis of the DLCs, we have excluded comparison star 2, as it was clearly variable on the scale of 0.03 mag with respect to the other 3 stars as well as the QSO. There is no formal indication of variance for the QSO, while star 1 may be variable at the 0.01 mag level. Quantitatively (based on the 5 pixel radius analysis), $P_{Q-1} = 0.9547, P_{Q-3} = 0.8101$, and $P_{Q-4} = 0.8250$, while $P_{1-3} > 0.99999, P_{1-4} = 0.9133$, and $P_{3-4} = 0.4860$. The lack of formal variability of the RQQSO, despite the presence of the two spikes noted above, is probably due to the very large number of otherwise very constant data points present in this set of DLCs.

To sum up, the example of this RQQSO underscores the point that all single-point correlated DLC variations must be examined very carefully, as we have done; one would trust that such efforts have been undertaken by other groups. Finally, we must take the entire dataset as an indication that this RQQSO is very possibly showing microvariability, and so it is definitely worthy of monitoring in the future.

0824+098. Yet another newly included RQQSO, it was followed for only about 3.3 hours on 1999 February 15. The DLCs for this observation are shown in Fig. 2. Here we have a very strong case for microvariability, as the quantitative statistical analysis yields: $P_{Q-1} > 0.999999, P_{Q-2} = 0.99926, P_{Q-3} = 0.99998$, and $P_{Q-4} > 0.999999$; while $P_{1-4} = 0.1012, P_{2-4} = 0.7263, P_{3-4} = 0.0075$ and all other star/star comparisons give formal probabilities of < 0.0001. (Star 4 is excluded from the plot as it is possibly a variable itself.) An examination of the DLCs shows that the bulk of the χ^2 for the QSO is produced by the single point at UT 17.53, where a rapid flare of about ~ 0.055 mag occurred. There is also an apparent rise in the quasar brightness by < 0.02 mag between UT 15.8 and 16.4. Although we see no reason to do so in this case, since there is no visible problem in any frame and no difference between photometry with different apertures, if one discards the single "flare" measurement, the statistical significance of the quasar fluctuations also vanishes. Again, while we are convinced that we have eliminated all plausible sources of error, since this apparent variability is a single-point fluctuation it cannot be considered completely convincing. Nonetheless, we consider this RQQSO to have very possibly shown an extremely rapid optical flare.

0946+301. In our observations of 1993 May 17 this RQQSO showed $\sim$0.05 mag correlated variations against all the 3 comparison stars over a period of about 1 hour (Paper II). Later observations on 1995 January 11 provided marginal evidence for a single point correlated variation of $\sim$0.03 mag in less than 10 minutes (Paper III).

Our new observations were taken on 4 nights, of which 3 nights yielded data of good quality (Fig. 3). For 1996 February 12 we have dense temporal sampling over more than 8 hours (Fig. 3a). Statistically significant variations of the QSO are not seen; however, significant variations involving star 2 are present, with $P_{1-2}, P_{2-3} > 0.999999$. They seem to arise mainly from the points at the beginning and end of the run when the airmass is high, but also partly from the small "glitch" seen at 21.6 UT. No correlated fluctuations involving the QSO were seen on that night. On the second night (1996 February 13, Fig. 3b) we again had good temporal coverage, lasting about 7 hours. Again, the formal statistical criterion does not indicate that the QSO varies, while formal variations of star 2 are present once again. On this night we see a small (∼0.02 mag) steady decline of the QSO intensity against all 3 comparison stars during the final 30 minutes of the observation; however, this may again be attributed to the large airmass. In the 2 hours of data taken on 1996 December 21 (Fig. 3c), no significant variations were noticed. The data from 1996 December 20 are very noisy and are not displayed.

Thus, on the whole, our new data provide no additional support to our earlier finding that 0946+301 very probably exhibits microvariability. This RQQSO does remain a prime candidate for additional monitoring.

1049−006. This source has exhibited possible microvariability in our earlier measurements of 1993 February 26 (Paper II), but equally extensive observations on two nights in 1994 showed no intranight variability (Paper III).

In the present series of observations (in both V and R filters) we again have fairly extensive temporal coverages, ranging from 4 to 5 hours on each of four nights. On 1996 March 28, we find $P_{Q-2} > 0.999999$ and, while the variations against stars 3 and 4 were not statistically strong (and star 1 was off the image that night), those χ^2 values were substantially above the ones arising from all the star-star DLCs. Less than two hours of usable data were obtained on 1996 April 24, and the results were quite noisy; no evidence for variability was present in that short data set, which is not shown. The observations on 1997 February 8 also showed no statistically significant fluctuations. The only other nominally significant variations of the QSO were recorded on 1997 February 9, when $P_{Q-2} = 0.99949$, $P_{Q-4} = 0.99781$; however, $P_{Q-1} = 0.724$ and $P_{Q-3} = 0.634$, so this too is not entirely convincing.

On the DLCs for 1049−006, displayed in Fig. 4, no strongly correlated variations of the QSO are evident. Hints of fluctuations that might account for the global statistical variability of the QSO appear between 18 and 19 UT on 1996 March 28, but these wiggles are not large enough to convince us of the presence of a real variation. Some indications of correlated DLCs for the QSO between 21 and 22 UT on 1997 February 8 are also present, but are even less convincing. So, despite the formal statistical significance of the variations against one or more stars on two of the four nights of our new data, we can still only call this source a possible microvariable.

1254+047. We had monitored this RQQSO only once before, on 1992 April 13; relatively poor conditions led to mediocre SNR and we found only a hint of microvariability (Paper I). On 1997 May 13 over 5 hours of densely sampled data were taken. There was no evidence for any fluctuations during this run, as shown in Fig. 5. Statistical measures of the probability of variation of the QSO against any of the 4 comparison stars, as well as between all pairs of comparison stars, were < 0.001.

1444+407. This RQQSO had been observed twice before by us in 1993 and 1994 and results were reported in Paper III. During the first observation, we found rather good evidence for the QSO dimming by ∼0.04 mag over the course of 0.5 hr, but only 2 hours of data were taken; a year later, only 1 hour of data was obtained and, unsurprisingly, no variations were seen.

We have now obtained roughly 3 hours of data on each of two consecutive nights: 1999 February 14 and 15 (Fig. 6). A statistical analysis of the first night yields possible variations for star 3, but not for the QSO, with the largest values $P_{3-4} = 0.9992, P_{3-5} = 0.9956, P_{1-3} = 0.9564, P_{1-4} = 0.8187, P_{1-5} = 0.7576$ but only $P_{Q-5} = 0.6418$ and $P_{Q-4} = 0.3759$. On the second night star 1 was seen to be noticeably variable, but so was the QSO: $P_{Q-1}, P_{Q-3}, P_{Q-4}, P_{Q-5}, P_{1-3}, P_{1-4} > 0.99999$, and $P_{1-5} = 0.99980$, while $P_{3-4} = 0.3711, P_{3-5} = 0.5193$ and $P_{4-5} = 0.1666$. Essentially all of the χ^2 for the QSO can be attributed to a major flare of ~ 0.16 mag at UT 23.64. Despite somewhat larger error bars for this point than any other, this is still a $> 5\sigma$ result and we see no reason to doubt this, other than the usual significant reservations applicable to all single-point events. Again, no difference in the images around this time are evident, and essentially identical DLCs result from plots produced using different photometric apertures. Therefore, we consider 1444+407 to be a prime example of a RQQSO showing a very rapid flare.

1630+377. This is one of the most frequently and densely observed RQQSOs in our programme. Three nights of data in 1993 provided no evidence for intranight variability (Paper II); however, on 1994 May 4, a highly significant dip of about 0.1 mag within less than 10 minutes was observed for the QSO, against all three comparison stars (Paper III). Unfortunately, no data points were available immediately following this dip for another 2 hours during which the filter was switched from R to V to B. Consequently, we could not place much confidence in this potentially remarkable feature.

On the night of 1996 May 20, the QSO was monitored over a span of more than 8 hours, with an additional $\sim$3 hours of data taken on the following night (Fig. 7). The comparison star 1 was clearly variable on both nights, so our analysis is restricted to examining the possible variation of the QSO relative to the stars 2 and 3. Statistical analysis of the DLCs yields a strong formal probability for this RQQSO exhibiting intranight variability. Explicitly, on 1996 May 20, $P_{Q-2} = 0.9990$ and $P_{Q-3} = 0.9876$, while $P_{2-3} = 0.9279$; on May 21, $P_{Q-2} > 0.999999$, $P_{Q-3} > 0.999999$, but $P_{2-3} = 0.691$. (As mentioned above, star 1 is clearly variable, with $P_{1-\mathrm{any}} > 0.999999$ on both nights). Still, no clear features are seen in the DLCs on either of the two nights. Possibly significant fluctuations do appear at 18.0 and 22.2 UT on May 20 and again at 21.1 UT on May 21, but again these are effectively limited to just one data point. Nonetheless, based on all the data available, we believe that the case for microvariability of this RQQSO now stands on a stronger footing than before.

4. Discussion and Conclusions

To facilitate an overview, a log of all the observations of RQQSOs in our programme is provided in Table 3. Among the cases designated as positive detections of microvariability we identify two classes: one with $P(\chi^2) > 0.999$ for DLCs of the RQQSO against all the comparison stars; the second with RQQSO DLCs apparently showing spike-like correlated excursions of at least 4σ amplitude. Examples of the later type from data presented in this paper are 0748+294, 0824+098, 1444+407, while our earlier work showed that 1630+377 was very possibly of this category. All of these DLCs are densely sampled, and have excellent SNRs. It is important to note that in no case do any of the comparison stars show similar spikes. Since the comparison stars outnumber these QSOs by a factor of 3, if these fluctuations were due to extrinsic events such as CR hits one would expect to see more such variations involving the stars than the QSOs, rather than none for the stars and several for the QSOs, as observed. Nonetheless, we note that any claims based on single point variations made with a single telescope cannot be utterly convincing, and this caveat remains regardless of the care and suspicion with which the authors analysed the data. Bearing in mind this caveat, for the purpose of global statistics, we shall combine both of these types of rapid variability in arriving at the following estimates.

Of the 16 bona-fide RQQSOs (i.e., excluding 0838+359, which is radio weak and already found by us to be a definite microvariable), it is seen that: 31% (5/16) are either probably or very probably microvariable, with four of these five having exhibited correlated spikes in their DLCs on at least one occasion; hints of rapid fluctuations have been noticed for another 31% (5/16), and the remaining 38% (6/16) RQQSOs have not shown any evidence for microvariability. It should be noted that the last categories include cases with very limited data spans and/or sparse sampling, so one may expect that additional monitoring could increase the fraction of RQQSOs showing intranight fluctuations. On the other hand, even the most probably variable RQQSOs did not show evidence of variability on every night they were monitored; however, this is true even for blazars (Carini 1990; Carini et al. 1991; Carini et al. 1992; Noble 1995; Heidt & Wagner 1996; Miller & Noble 1996).

Confining attention to the extended light curves available in our data, we have thus far obtained a total of 15 essentially continuous light curves spanning more than 4 hours. These pertain to seven RQQSOs, namely, 0748+294, 0946+301, 1049−006, 1206+459, 1352+011, 1522+102 and 1630+377 (Papers II, III and IV). DLCs of these RQQSOs taken on 13 of the 15 nights span a duration between 6 and 8.5 hours. The sampling rate is dense (5 to 10 data points per hour) for the 8 sets of DLCs reported in Papers III and IV and about half as dense for the remaining 7 sets of DLCs reported in Paper II. It is interesting that none of the 15 sets of DLCs shows a clearly discernible variability event exhibiting a steady trend sustained over at least an hour at a rate of ~ 0.03 mag/hour, or more. Many such events have been recorded in the intranight monitoring of several BL Lac objects whose emission is believed to be intrinsically weak but appears strongly Doppler boosted (e.g., Carini et al. 1992 and references therein; Wagner et al. 1993; Urry et al. 1997; Ghisellini et al. 1997).

Several other groups have recently joined in the search for microvariability in radio quiet AGN. The first published study of microvariability of a significant sample of radio quiet AGN other than ours has been reported by Jang & Miller (1995; 1997). They found that only 3 of 19 objects observed clearly showed microvariability. This fraction is distinctly smaller than what they found for radio loud objects of similar optical brightnesses, which led them to assert that the radio quiet objects were less likely to show rapid variability. Their analysis of errors and standards for definition of variations (99% confidence) are somewhat different from ours, but an examination of their results using our approach would certainly lead to very similar conclusions. Nonetheless, a direct comparison of our results with theirs is not strictly proper, since the Jang & Miller sample includes many intrinsically weak and relatively nearby AGN (e.g., Seyfert galaxies), and there is some evidence that the degree of RQ AGN variability may be negatively correlated with luminosity and positively correlated with distance (e.g., Cid Fernandes, Aretxaga & Terlevich 1996).

Recently, de Diego et al. (1998) have addressed any differences between radio loud and radio quiet quasars directly, by considering a sample of 34 objects, equally split between core dominated RLQSOs and RQQSOs; they observed pairs of objects from each category, reasonably matched in luminosities and redshifts. Unfortunately, each object was measured only for several short periods during a night, with each measurement consisting of five 1-minute exposures. Only one comparison star was typically used, and most objects were looked at only on one or two nights. A unique analysis of variance (ANOVA) approach, which groups the small number of contiguous data points was employed to interpret the data, which de Diego et al. argue can provide better error estimates than does the standard approach; however, their approach sacrifices the continuity of the lengthy data trains used in our work and that of Miller and collaborators. Using a 3σ level to define detections, 5 of 17 objects in each sample were claimed to have exhibited microvariability. Thus, they claim their results to be consistent with no difference in frequency of rapid variability between the radio loud and radio quiet QSOs.

Romero, Cellone & Combi (1999) have extended the efforts of Jang & Miller to the southern sky, and examined a sample of 23 AGN: 8 RQQSOs, 5 RLQSOs, 7 radio selected BL Lacs, and 3 X-ray selected BL Lacs. Their analysis used the scatter in a weighted averages of 6 comparison stars to estimate errors, but the same criterion for variability as did Jang & Miller (1995). None of their 8 RQQSOs showed much evidence of intranight variability, while 3 of 5 RLQSOs were microvariable at the levels allowed for by their SNR; for comparison, 5 of 7 radio selected BL Lacs and 1 of 3 X-ray selected BL Lacs satisfied this variability criterion. Romero et al. (1999) then combined their data with that of Miller & Jang to produce rather rough estimates for duty cycles of microvariability for different types of AGN, ranging from $\sim$3% for RQQSOs to $\sim$70% for RLQSOs (including radio-selected BL Lacs). They also provide a critique of the approach taken by de Diego et al. (1998), particularly noting the difficulties induced by using only a single comparison star to define errors. Given the substantial number of comparison stars we have found to be variable on these short timescales, we echo Romero et al.'s critique of the work of de Diego et al.

A variability study of 22 Seyfert 1 galaxies has recently been conducted by Petrucci et al. (1999). They use a (differently from Romero et al.) weighted average of 3 or more comparison stars to define a "virtual" standard star and use a structure function approach to look for any continuous (longer intranight) trends in the data. In no case do they find any evidence for microvariability (or intranight variability) in any of these relatively weak, radio quiet AGN.

A search for rapid optical variability in two broad absorption line QSOs (BALQSOs) has recently been conducted by Anupama & Chokshi (1998). They claim to have seen significant variations in each of the two QSOs (like most BALQSOs, these two are apparently presumed to be radio quiet). However, the significance level of the variations is only 95% for the QSO 0846+156 (Anupama & Chokshi 1998), and an application of our stricter criteria to their published light curves would allow us to classify it as only a possible variable. Their data for 0856+172 give a somewhat stronger indication for rapid fluctuations, making it a probable variable in our terminology. They also draw attention to an apparent, sharp drop of one magnitude in the DLC of this QSO, within about 15 minutes, with an equally rapid rise to almost the original intensity level. This sharp drop is considerably larger than even the large dip seen in our monitoring of the RQQSO 1630+377 on the night of May, 4, 1994 (Paper III). As remarked by us in Paper III and below, the reality of such immense fluctuations involving just a single data point needs to be ascertained by further monitoring.

We note that in general, theoretical models can more easily account for relatively substantial *positive* fluctuations (such as we have reported in our data here) than they can explain large negative spikes. Clearly, however, if confirmed, all such strong ultra-rapid variations may have serious implications, since one would then be sampling time scales approaching the light crossing time for the Schwarzschild radius of a $10^8 M\odot$ black hole and the energies involved are several percent of the stupendously high luminosities of these QSOs. Thus, confirmed detections of such events would place heavy demands on the starburst model for RQQSOs (see, Cid Fernandes et al. 1996). In our view, the reality of all such spikes remains to be absolutely established, e.g., *via* an even more dense temporal monitoring with sufficiently large telescopes, preferably simultaneously at more than one site.

It is very difficult to make exact comparisons between the results of these different studies, in that each of them uses different sample selection criteria, different techniques to search for microvariability and varying standards of strictness in claiming detections. Over all, our work provides by far the most dense and extensive temporal sampling for RQQSOs. It is not very meaningful to attempt a detailed statistical analysis of the combined published data because of the different ways in which it has been analysed and presented. Nonetheless, a few key conclusions appear to emerge from our study and those others summarized above.

First, the weight of available evidence strongly suggests that RQQSOs are less likely to exhibit microvariability in a given time-span than are radio loud AGN, though the claims of de Diego et al. (1998) indicate that this conclusion is not yet definitive. Second, there is now good evidence that these highly luminous radio quiet AGN do show *some* fluctuations. While the duty cycle estimates obtained by Romero et al. (1999) are certainly only approximate, particularly given the limited number of sources and observation times involved, the low value found for RQQSOs is in accord with our observations. *However, the character of these rapid variations in RQQSOs seems* *to us to be quite different from that of radio loud AGN.* Essentially all of the variations we have judged to be statistically significant are very brief, consisting of changes restored within at most 30 minutes. In several cases the RQQSOs appear to evince fluctuations of $\geq$0.05 mag, but as they are confined to single points in the DLCs, we reiterate that they are inherently suspect, although we again note that this type of variation has not been seen in the comparison stars monitored simultaneously (even though they are a few times more numerous). While similarly brief flares have been recorded in the light curves of blazars (e.g., BL Lac, Miller et al. 1989; Ap Lib, Carini et al. 1991), those objects also show fluctuations on much wider ranges of temporal and magnitude scales.

To be absolutely convincing, simultaneous observations of very rapid flares from two different locations would be required, since then extraneous (e.g., CR hit) explanations would be ruled out. Despite a considerable amount of earlier evidence, it is fair to say that the general acceptance of optical microvariability in blazars only followed the publication of simultaneous data in excellent agreement from Kitt Peak and Lowell observatories for OQ 530 (Carini, Miller & Goodrich 1990). Therefore, despite the difficulty in coordinating such work, in the current observing season we are attempting to obtain simultaneous observations of some RQQSOs from both the VBT and UPSO.

As discussed in Papers I and II, intranight optical variability can be a key observable to address the basic issue of the energy source in QSOs (see also Gopal-Krishna, Sagar & Wiita 1993a). Given the widespread perception that most radio quiet objects lack relativistic jets, the likely source of these small fluctuations are the accretion disks that almost certainly exist around central supermassive black holes. We have now collected enough data to be able to strongly infer that at least some RQQSOs do exhibit microvariability, albeit less often, typically for shorter times, and usually less violently than do radio-loud quasars and blazars (cf. Jang & Miller 1997; Romero et al. 1999). Additional data are being acquired to make this comparison more quantitative.

Further, as discussed in Paper II, there are at least two main competing hypotheses for this difference. Firstly, it is conceivable that even the virtually radio-silent QSOs we have considered here possess incipient nuclear jets (e.g., Falcke et al. 1996a, b; Blundell & Beasley 1998; Sect. 1). In this scenario, it is possible that radio loud and radio quiet objects eject electron-positron and electron-proton jets, respectively (Falcke, Malkan & Biermann 1995), thereby explaining the difference. Alternatively, we might be witnessing an extreme version of the starburst phenomenon in the radio quiet quasars (e.g., Terlevich et al. 1992), but the brief time scales and extreme energetics remain very hard to reconcile with this possibility.

Secondly, making the usual assumption (discussed in Paper II, and consistent with the deficiency of optical polarization; e.g., Impey & Tapia 1990; Wills 1991), that radio-quiet QSOs lack relativistic jets, such short time scales are unlikely to arise from relativistic time compression, nor could they be due to external effects such as superluminal micro-lensing (cf. Gopal-Krishna & Subramanian 1991). They would hence be intrinsic to the QSO. Suggested theoretical scenarios involve accretion disk flares or shocks (e.g., Zhang & Bao 1991; Wiita et al. 1992; Chakrabarti &

Wiita 1993; Mangalam & Wiita 1993); however, to explain substantial fluctuations in the very brief temporal intervals observed, it might then be necessary to invoke coherent radiation processes (e.g., Benford 1992; Krishan & Wiita 1990, 1994; Lesch & Pohl 1992; Benford & Lesch 1998). Unambiguous detection of substantial, yet very quick, fluctuations in the RQQSO luminosity would favour the origin of at least some of the variability in relativistic jets, and a model along the lines of Falcke et al. (1995) would be a strong contender, provided the plausibility of coherent radiation can be challenged through independent arguments.

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Table 1. Recent optical monitoring of radio quiet QSOs

IAU name*	z	m_V	M_V	Date of observations	Filter	Telescope
$0946+301$	1.216	16.38	-28.6	12. 02. 1996	R	2.34m VBT
$0946+301$	1.216	16.38	-28.6	13. 02. 1996	R	2.34m VBT
$1049-006$	0.357	16.04	-25.8	28. 03. 1996	R	2.34m VBT
$1049-006$	0.357	16.04	-25.8	24. 04. 1996	R	2.34m VBT
$1630+377$	1.466	16.07	-29.5	20. 05. 1996	R	2.34m VBT
$1630+377$	1.466	16.07	-29.5	21. 05. 1996	R	2.34m VBT
$0043+039$	0.385	15.88	-26.1	20. 12. 1996	V	1.04m UPSO
$0946+301$	1.216	16.38	-28.6	20. 12. 1996	R	1.04m UPSO
$0043+039$	0.385	15.88	-26.1	21. 12. 1996	V	1.04m UPSO
$0946+301$	1.216	16.38	-28.6	21. 12. 1996	R	1.04m UPSO
$1049-006$	0.357	16.04	-25.8	08. 02. 1997	V	2.34m VBT
$1049-006$	0.357	16.04	-25.8	09. 02. 1997	V	2.34m VBT
$1254+047$	1.024	16.10	-28.1	13. 05. 1997	R	2.34m VBT
$0748+294$	0.910	15.00	-29.0	14. 02. 1999	R	1.04m UPSO
$1444+407$	0.267	15.74	-25.4	14. 02. 1999	R	1.04m UPSO
$0824+098$	0.260	15.50	-25.6	15. 02. 1999	R	1.04m UPSO
$1444+407$	0.267	15.74	-25.4	15. 02. 1999	R	1.04m UPSO

* Based on coordinates defined for 1950.0 epoch.

Table 2. Comparison star locations (relative to the QSOs)

QSO	Star 1		Star 2		Star 3		Star 4		Star 5	
	Δr(″)	PA(°)	Δr(″)	PA(°)	Δr(″)	PA(°)	Δr(″)	PA(°)	Δr(″)	PA(°)
0043+039	138	128	114	260	189	347	256	7		
0748+294	97	341	165	318	119	180	128	264		
0824+098	97	42	41	78	56	195	85	177		
0946+301	39	165	73	253	174	323				
1049−006	215	110	92	146	82	182	53	145		
1254+047	126	32	60	210	138	215	247	149		
1444+407	223	116	249	124	157	152	150	42	131	57
1630+377	106	68	102	34	92	150				

Table 3. Summary of our monitoring programme's results

QSO	Date	Band	Telescope	Paper	Duration (hr)	Microvariability status
0043 + 039	20.12.96	V	UPSO	IV	2	none seen (noisy)
	21.12.96	V	UPSO	IV	3	none seen (noisy)
0117 + 213	12.11.93	R	VBT	III	5.5	possible
	13.11.93	R	VBT	III	3	possible
0530 − 379	20.12.91	V	Dutch	GKWA	2	none seen
	21.12.91	V	Dutch	GKWA	1	none seen
	25.12.91	V	NTT	GKWA	4	none seen
0540 − 389	25.12.91	V	NTT	GKWA	3	none seen
0748 + 294	14.02.99	R	UPSO	IV	6.5	probable (spikes)
0824 + 098	15.02.99	R	UPSO	IV	3	probable (spikes)
0838 + 359	23.01.93	V	VBT	II	(1 point)	none seen
	24.01.93	V	VBT	II	7	possible
	25.01.93	V	VBT	II	5	probable
	26.01.93	V	VBT	II	(2 points)	none seen
	27.02.93	V	VBT	II	2	yes
	12.11.93	R	VBT	III	(2 points)	none seen
	13.11.93	R	VBT	III	(1 point)	none seen
	18.12.93	R	VBT	III	4	none seen
0946 + 301	24.01.93	V	VBT	II	8	none seen
	25.01.93	V	VBT	II	5	none seen
	26.01.93	V	VBT	II	(3 points)	none seen
	17.05.93	R	VBT	II	2.5	very probable
	11.01.95	R	VBT	III	4.5	possible
	12.02.96	R	VBT	IV	8.5	none seen
	13.02.96	R	VBT	IV	7	possible
	20.12.96	R	UPSO	IV	2	none seen (noisy)
	21.12.96	R	UPSO	IV	2	none seen
1049 − 006	26.02.93	V	VBT	II	7	possible
	22.04.93	V	VBT	II	(1 point)	none seen
	10.03.94	R	VBT	III	7	none seen
	11.03.94	R	VBT	III	8	none seen
	28.03.96	R	VBT	IV	4.5	possible
	24.04.96	R	VBT	IV	3	none seen (noisy)
	08.02.97	V	VBT	IV	3.5	possible
	09.02.97	V	VBT	IV	3	possible

$1206+459$	11.04.92	V	VBT	I	5	none seen
	26.02.93	V	VBT	II	(1 point)	none seen
	27.02.93	V	VBT	II	7	none seen
	23.04.93	R	VBT	II	7	possible
	19.02.94	R	VBT	III	2.5	none seen
	20.02.94	R	VBT	III	5	none seen
	06.03.94	R	VBT	III	1.5	none seen
	07.03.94	R	VBT	III	2	none seen
	11.03.94	R	VBT	III	(3 points)	none seen
	30.03.95	R	VBT	III		none seen (noisy)
	31.03.95	R	VBT	III		none seen (noisy)
$1248+401$	12.04.92	V	VBT	I	5	none seen
$1254+047$	13.04.92	V	VBT	I	5	hint (sparse sampling)
	13.05.97	R	VBT	IV	5	none seen
$1338+416$	12.04.92	V	VBT	I	5	none seen
$1352+011$	13.04.92	V	VBT	I	4	hint (sparse sampling)
	21.04.93	R	VBT	II	7	none seen
$1444+407$	23.04.93	R	VBT	III	2	probable
	09.04.94	R	VBT	III	1	none seen (sparse sampling)
	02.14.99	R	UPSO	IV	2.5	none seen
	02.14.99	R	UPSO	IV	3	probable (spike)
$1522+102$	22.04.93	R	VBT	II	8	none seen
$1630+377$	15.05.93	R	VBT	II	2	none seen
	16.05.93	R	VBT	II	2	none seen
	17.05.93	R	VBT	II	6	none seen
	04.05.94	R	VBT	III	5	possible (spike)
	05.05.94	R	VBT	III	4.5	none seen
	04.06.94	R	VBT	III	4.5	none seen
	20.05.96	R	VBT	IV	7	very probable (spike)
	21.05.96	R	VBT	IV	2.5	possible

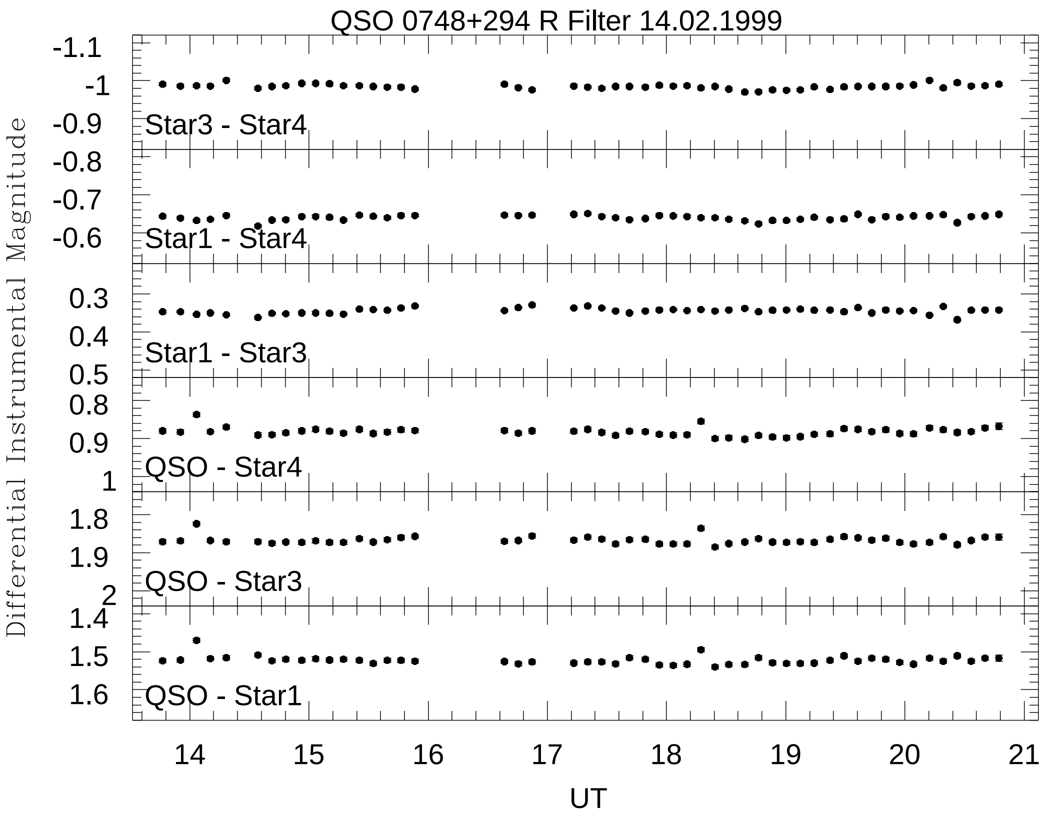

Fig. 1.— Figure 1a. Differential light curves (DLCs) for the RQQSO 0748+294 on 1999 February 14; stars 1, 3, and 4 are compared in this figure: a) reduced using 7 pixel aperture radii; b) reduced using 5 pixel aperture radii. NOTE THAT SOME OF THESE FIGURES MAY NOT APPEAR VISIBLE THROUGH GHOSTVIEW BUT THEY SHOULD PRINT OUT OK IN HARD-COPY.

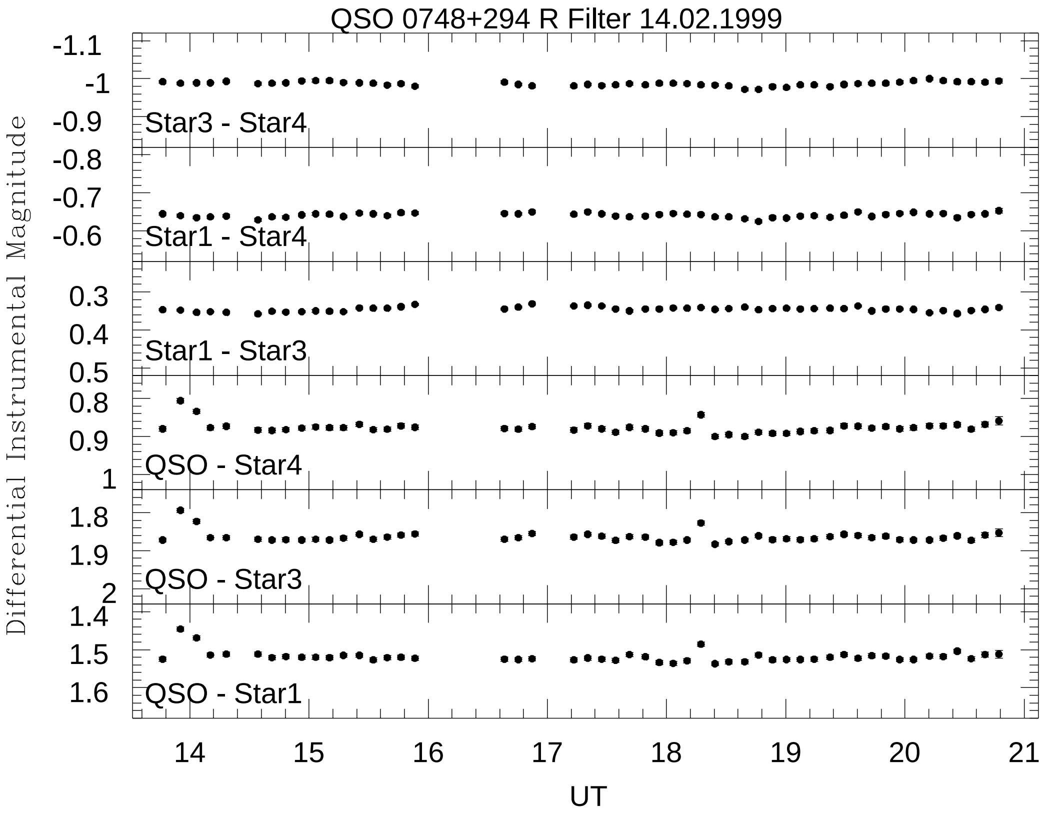

Fig. 2.— Figure 1b

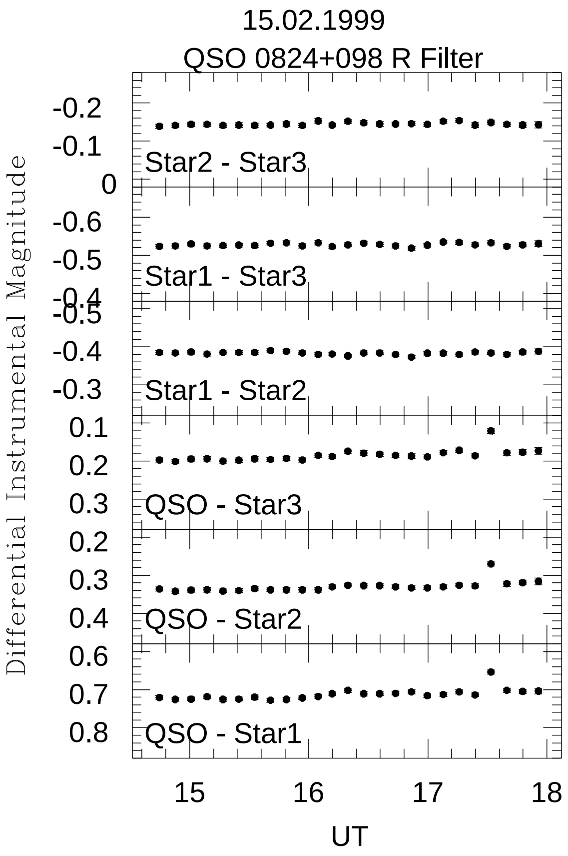

Fig. 3.— Figure 2. DLCs for the RQQSO 0824+098 on 1999 February 15.

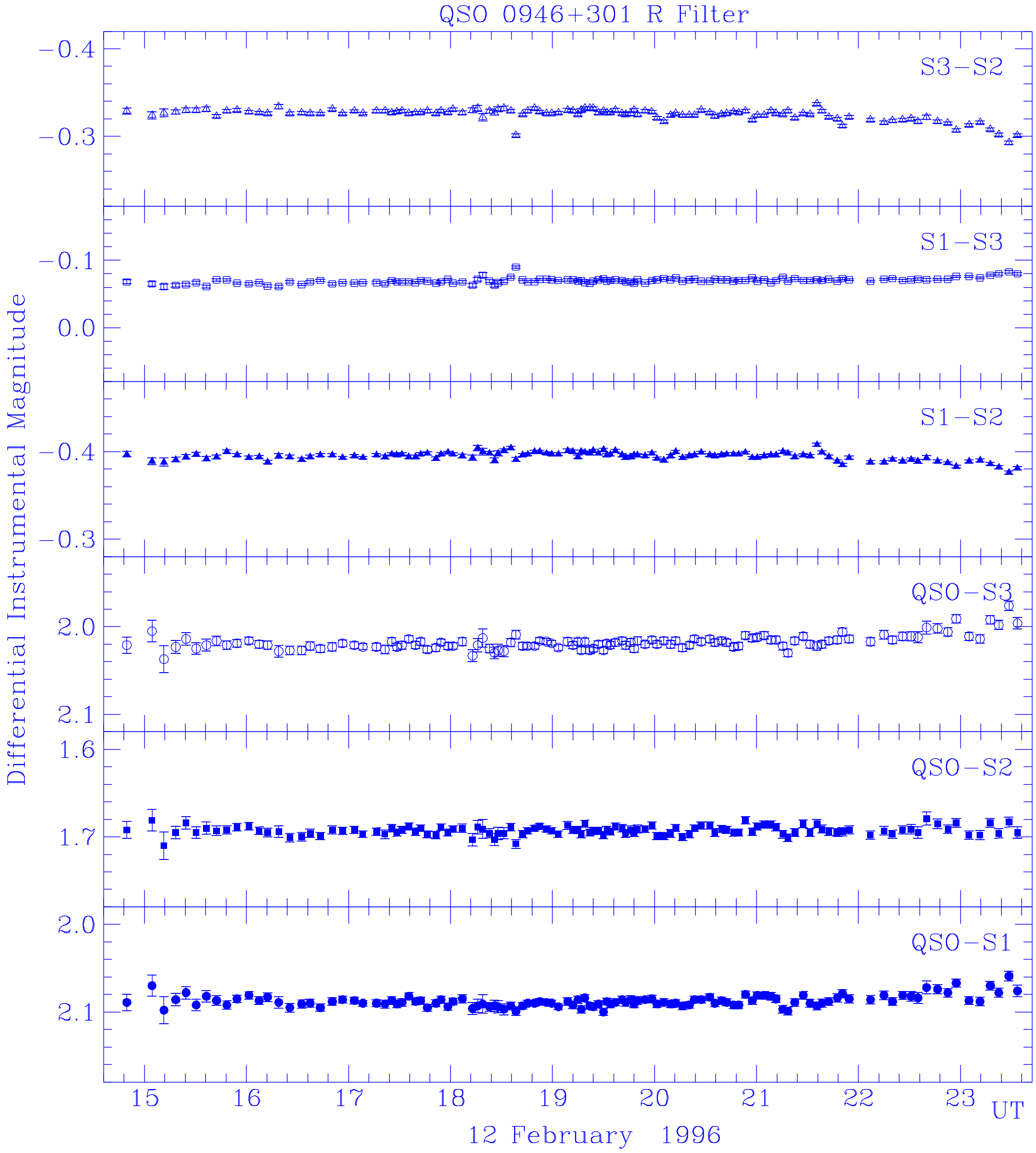

Fig. 4.— Figure 3a. DLCs for RQQSO 0946+301: a) 1996 February 12; b) 1996 February 13; c) 1996 December 21.

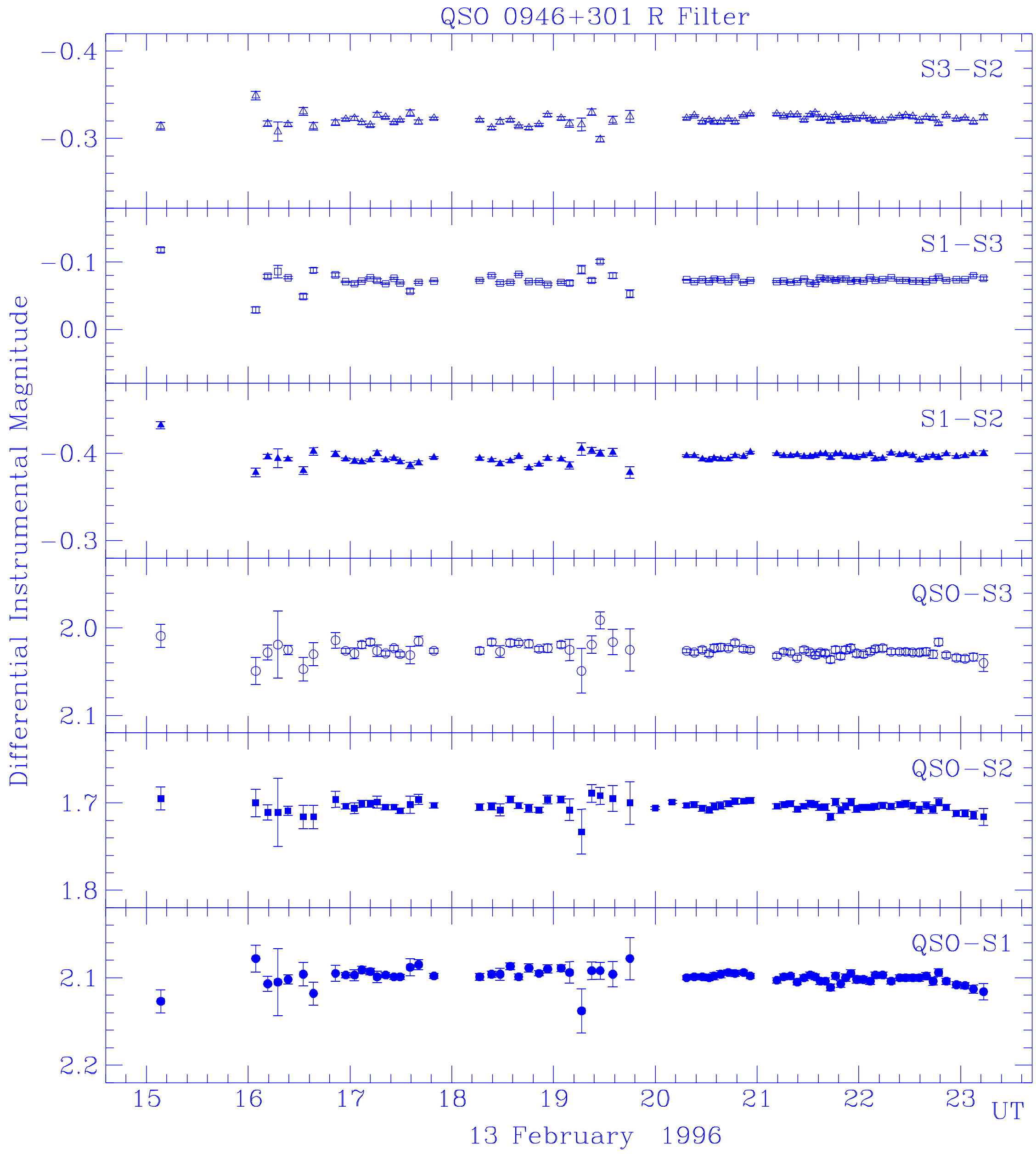

Fig. 5.— Figure 3b.

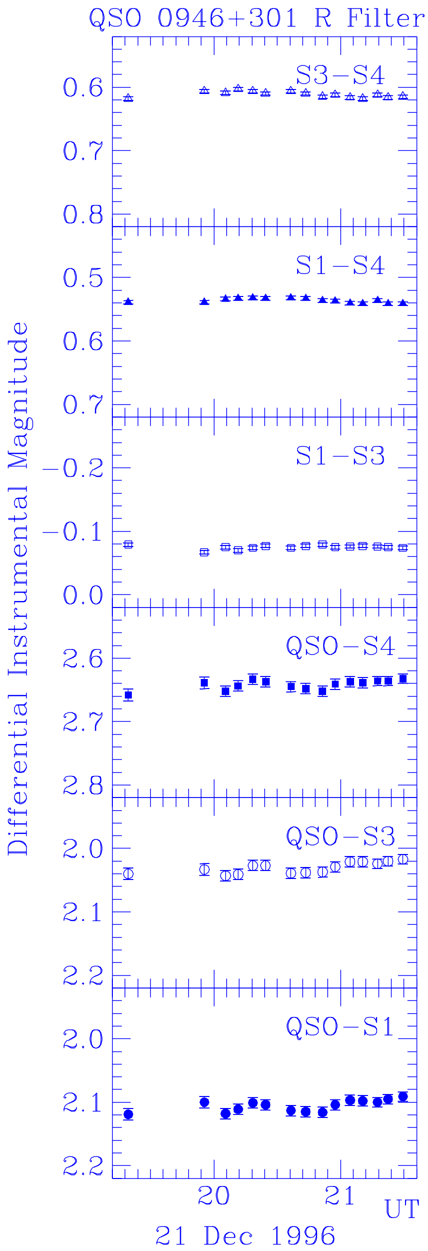

Fig. 6.— Figure 3c.

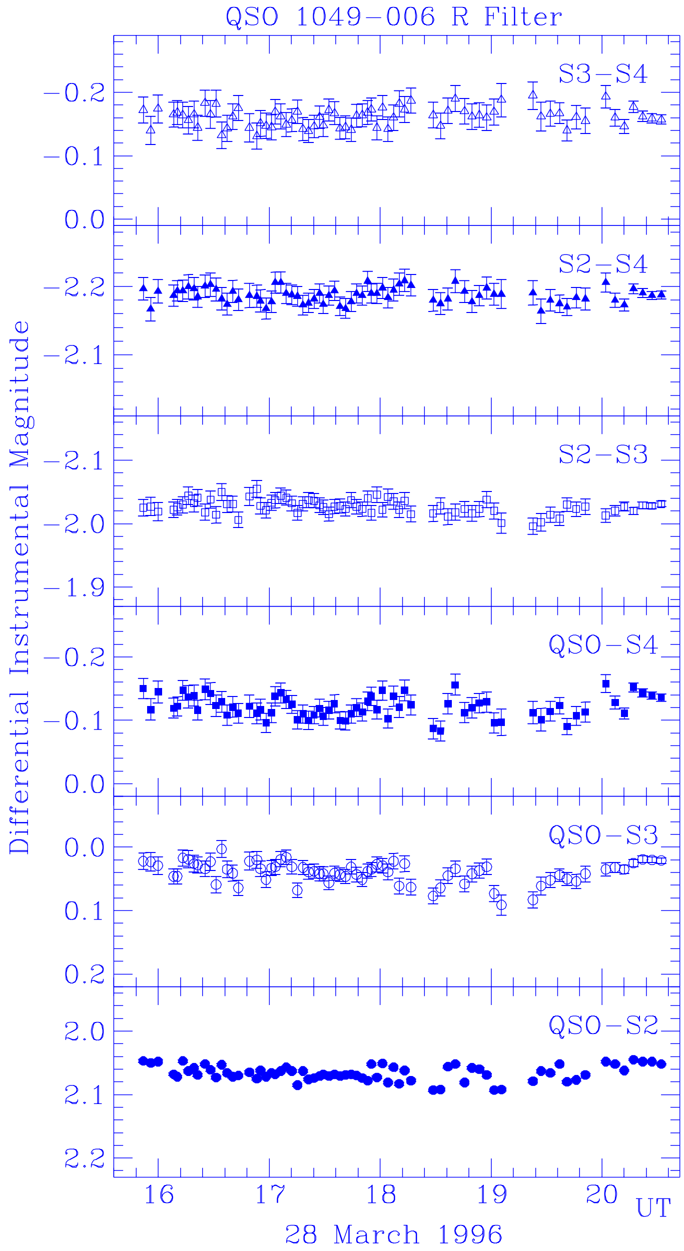

Fig. 7.— Figure 4a. DLCs for RQQSO 1049−006: a) 1996 March 28; b) 1997 February 8; c) 1997 February 9. In panel a) star 4 is displayed instead of star 1.

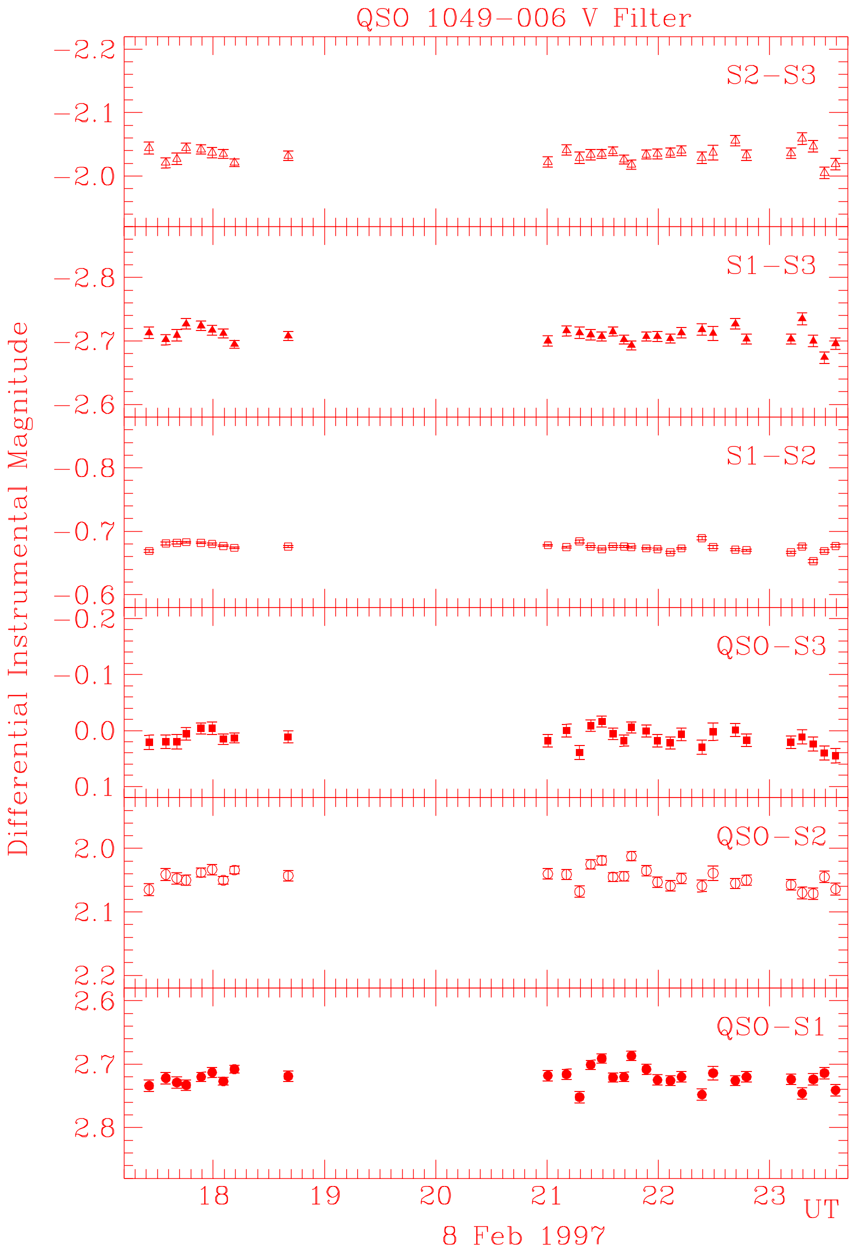

Fig. 8.— Figure 4b.

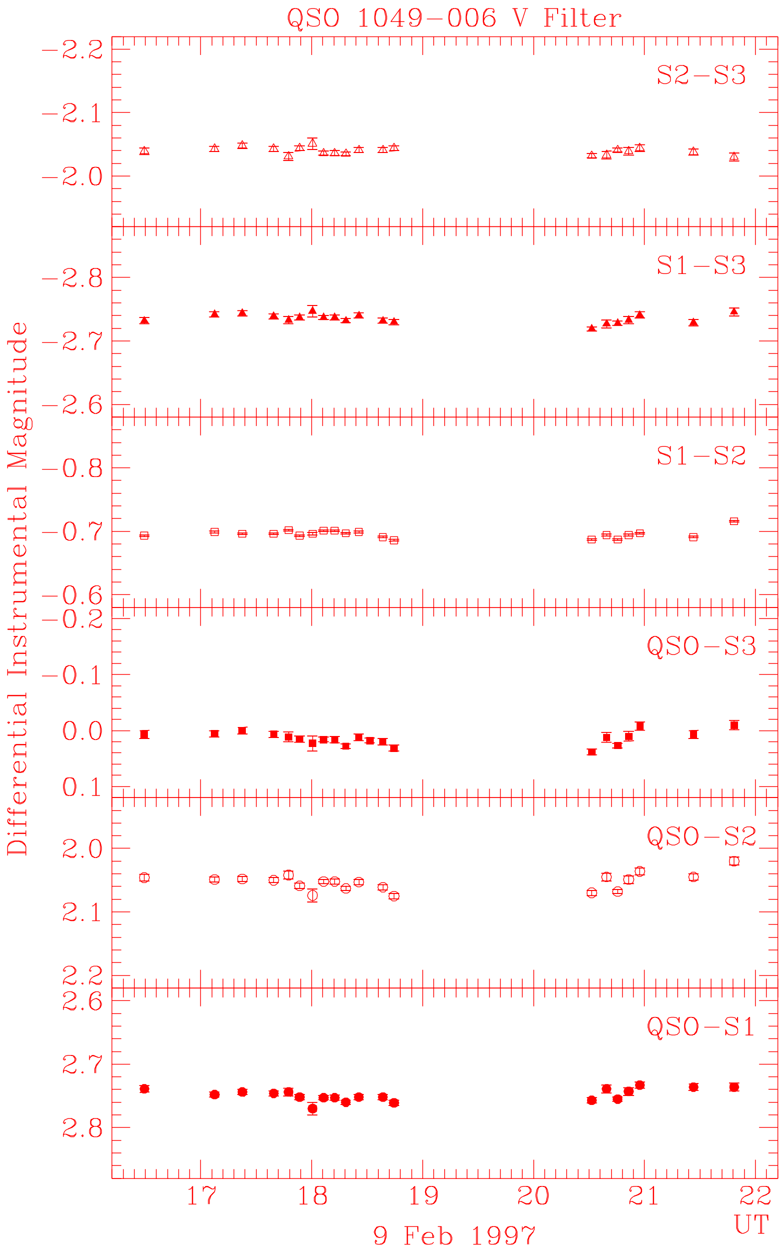

Fig. 9.— Figure 4c.

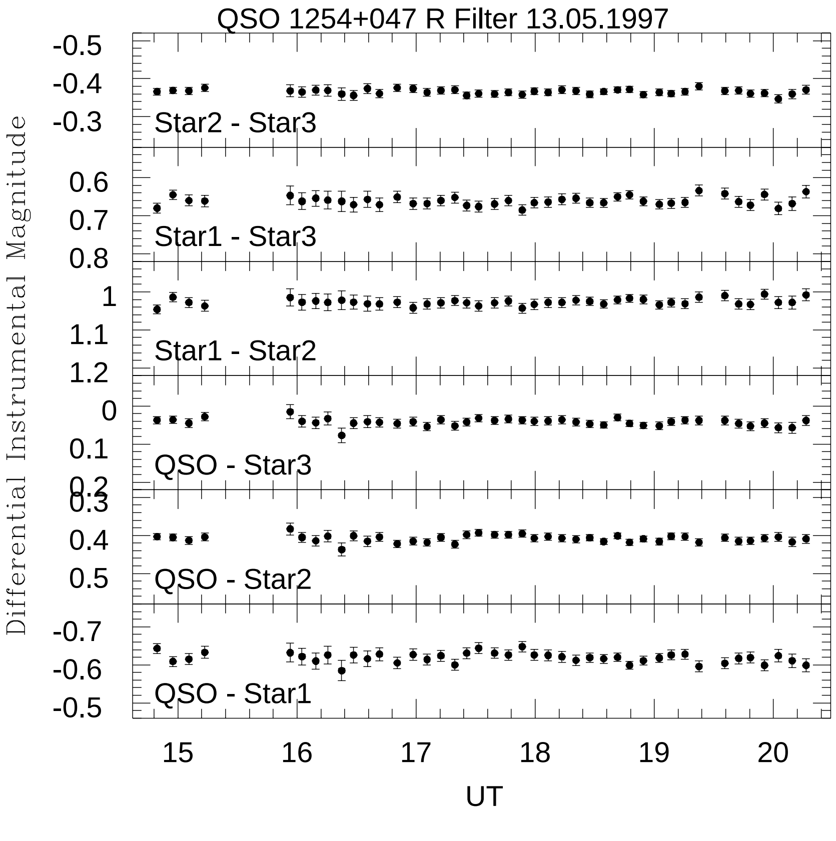

Fig. 10.— Figure 5. DLCs for the RQQSO 1254+047 on 1997 May 5.

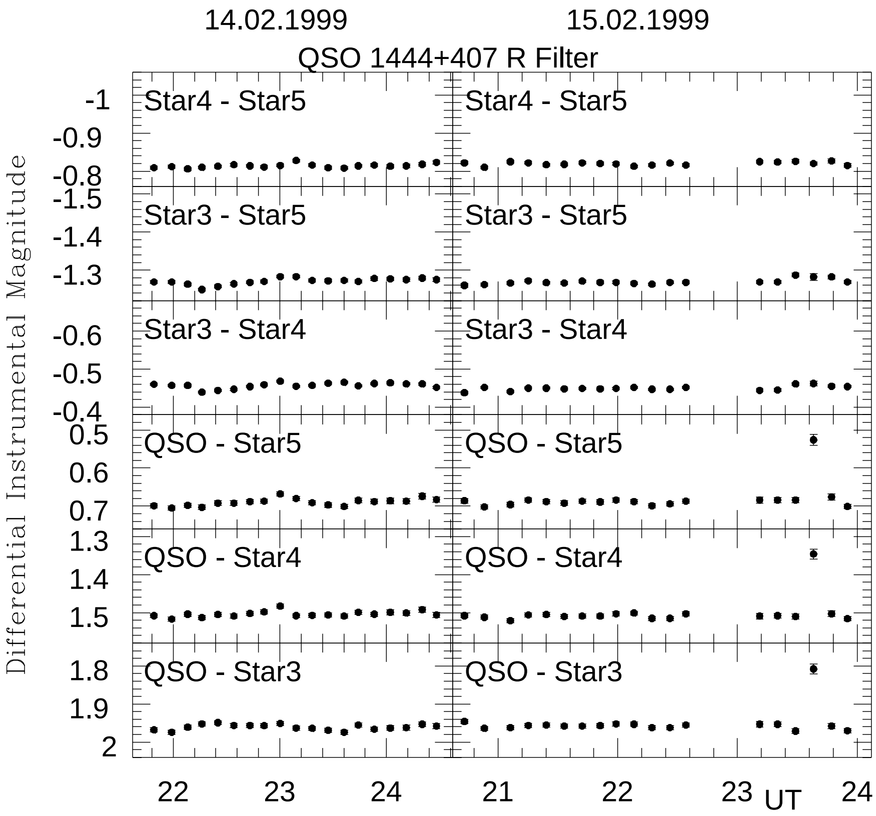

Fig. 11.— Figure 6. DLCs for the RQQSO 1444+407 on 1999 February 14 and 15; stars 3, 4, and 5 are displayed.

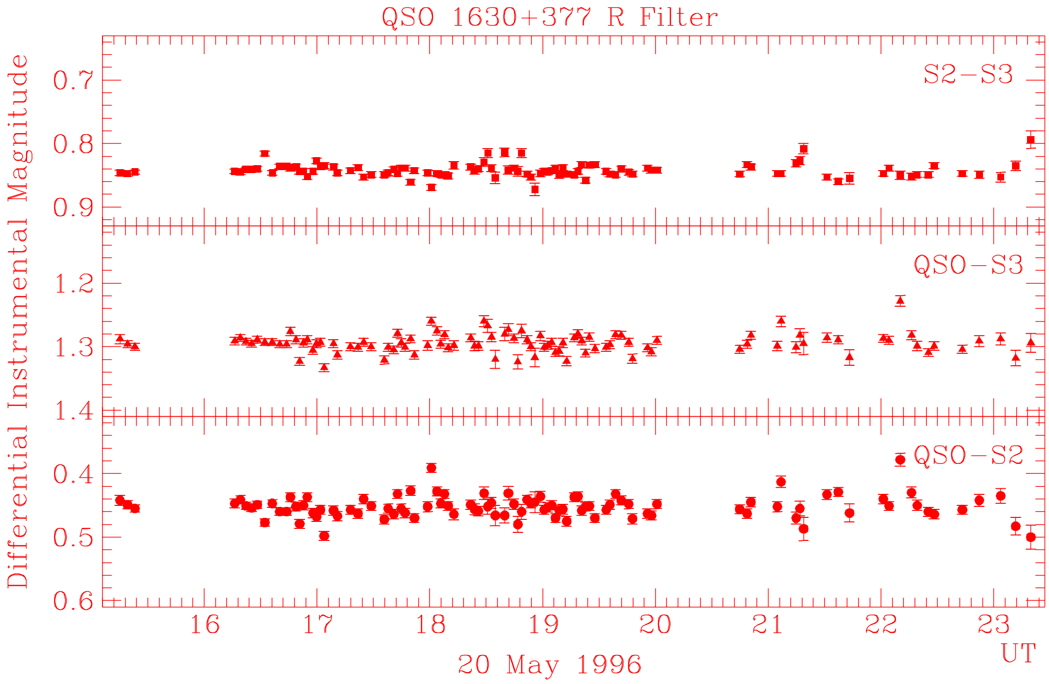

Fig. 12.— Figure 7a. DLCs for RQQSO 1630+377: a) 1996 May 20; b) 1996 May 21. As star 1 was clearly variable, only data for stars 2 and 3 are shown.

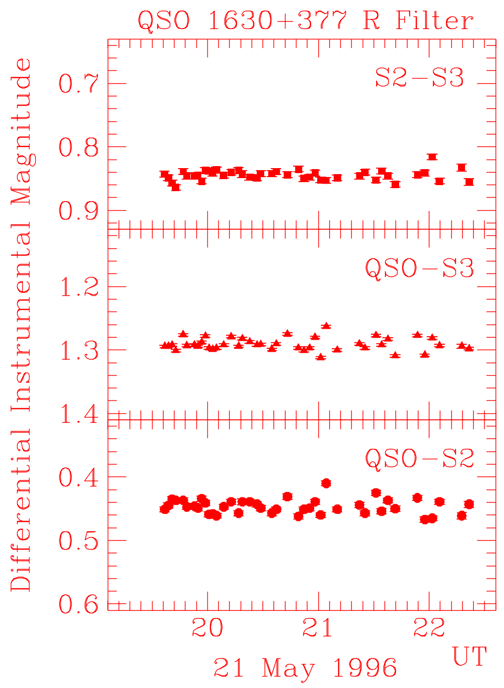

Fig. 13.— Figure 7b.