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A search for intra-night optical variability in radio-quiet QSOs

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ABSTRACT

We report results from a new programme, using the 2.34-m Vainu Bappu Telescope, to search for intra-night optical variability in five QSOs which are radio-quiet but optically bright and luminous. Our limited data show mild indications of microvariability for some of the sources, but in no case has the reality of the fluctuations been clearly established. Additional observations of these and other QSOs could provide a powerful means of discriminating between various theoretical mechanisms proposed for the origin of optical microvariability in active galactic nuclei. Clear detections of microvariability in radio-quiet QSOs would favour models in which flares on accretion discs are responsible for the microvariability, while a demonstration that such fluctuations are extremely rare would support models based on shocks propagating down the relativistic jets which are only associated with radio-loud active galactic nuclei.

Key words: galaxies: active – galaxies: photometry – quasars: general.

1 INTRODUCTION

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; Miller & Carini 1991; Carini et al. 1991, 1992; Miller et al. 1992; Wagner 1992). Many of these blazars also show significant intra-day variability in the centimetre radio band (e.g Quirrenbach et al. 1989, 1992; Krichbaum, Quirrenbach & Witzel 1992). Many of the radio variations seem to show a preference for time-scales of order a day (Heeschen 1984; Quirrenbach et al. 1989, 1992). So far, ultraviolet microvariability has been confirmed for only one source, PKS 2155 − 304, in which the *IUE* UV flux was observed to change by ~10 per cent in one day (Edelson et al. 1991; Miller et al. 1992). Simultaneous observations in the V band indicate changes of comparable magnitude (Miller et al. 1992). Seyfert galaxies and other active galactic nuclei (AGN) have long been known often to show substantial variability on time-scales of much less than a day in the X-ray band (e.g. Treves et al. 1982; Lawrence et al. 1987; McHardy 1989). However, no systematic searches for optical microvariability in radio-quiet quasi-stellar objects (RQQSOs) have been reported. A first study using two southern RQQSOs, 0530 − 37 and 0540 − 38, has very recently been performed (Gopal-Krishna, Wiita & Altieri 1993), but no clear evidence of flux variations down to the ≈ 2–3 per cent level was found over the course of a night for either of these objects.

Theoretical explanations of microvariability fall broadly into 'extrinsic' and 'intrinsic' categories. A commonly invoked extrinsic mechanism is refractive interstellar scintillation, although this would only be relevant in the radio band. While a recent statistical analysis of radio fluctuations of an entire sample of compact flat-spectrum radio sources is consistent with interstellar scintillation (Quirrenbach et al. 1992), this mechanism seems to be unable to account for the simultaneity and similar amplitude of the variations over a large range of radio frequencies which is observed in some cases (Qian et al. 1991). 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. It seems statistically unlikely, however, that this mechanism is applicable to a large fraction of AGN, and it thus probably would not be the dominant mechanism if this microvariability phenomenon were found to be ubiquitous.

Intrinsic explanations include 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

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variable (Gopal-Krishna & Wiita 1992). A related model involves non-axisymmetric bubbles carried outward in relativistic magnetized jets (Camenzind & Krockenberger 1992). Plasma processes, both incoherent (Krishan & Wiita 1993) and coherent (Baker et al. 1988; Benford 1992; Krishan & Wiita 1990, 1993; Lesch & Pohl 1992) might also play important roles, but nearly all of these models also incorporate relativistic jets. Another family of intrinsic explanations invokes numerous flares or hotspots on the surface of 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 the rapid X-ray variations of blazars (e.g. Abramowicz et al. 1991; Zhang & Bao 1991).

Because radio-quiet AGN are not believed to eject relativistic jets (e.g. Terlevich, Melnick & Moles 1987; Antonucci, Barvainis & Alloin 1990), unlike blazars in which jets are expected to dominate the emission (e.g. Urry & Padovani 1991; Bregman 1992), any evidence for microvariability in radio-quiet AGN would provide substantial support for the models involving a hotspot on the accretion disc. So far, nearly all quasars searched for microvariability in the optical or radio have been core-dominated radio sources which are known to vary by large amounts over time-scales that are longer than microvariability time-scales. A few Seyfert galaxies have been monitored using CCD detectors as *N*-star photometers, but with negative results; this lack of detection of variations could, however, easily be due to the short durations of most of these observations (Miller, private communication). 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 the former is already known to have a mini-blazar-type nucleus (Wilson & Ulvestad 1982), while the latter also has a compact non-thermal radio source at its nucleus (Ulvestad, Wilson & Sramek 1981); further, these measurements did not employ the most modern instrumentation, and are prone to systematic errors due to contamination from the circumnuclear emission. Done et al. (1990) monitored the Seyfert 1 galaxy NGC 4051 simultaneously in the X-ray and *B* bands, finding no variation in the latter band even while substantial X-ray flares were being detected; this source has been more recently examined in the *K* band by Hunt et al. (1992), who discovered a marginal variation on one night and no detectable change on another.

In the light of the above discussion, the most secure test of the accretion disc model for intra-night variation would come from optical monitoring of QSOs which are radio-quiet but optically powerful (and hence point-like), using wide-field CCD arrays which would encompass several suitable comparison stars on each frame. Here we present preliminary results from such a programme of observations.

2 OBSERVATIONS

We chose the QSOs to be examined from the lists of Hewitt & Burbidge (1987) and Véron-Cetty & Véron (1989), using the following criteria: (i) $M_V \ll -23$, so that we are definitely dealing with luminous QSOs and not with Seyfert galaxies; (ii) a radio flux at 5 GHz of less than 0.5 mJy (Kellermann et al. 1989), so that these objects are indeed radio-quiet and are thus unlikely to have a significant fraction of their emission emanating from jets; (iii) $m_V \approx 16$, which is bright enough to allow good signal-to-noise ratios to be attained in exposures of ~ 10 min; (iv) at least two or three stars of roughly comparable apparent magnitude located within the CCD frame encompassing the QSO, thus allowing us to identify and discount any of the comparison stars that are themselves variable on short time-scales; and (v) a right ascension in the range that allows monitoring for about 6 h over a night, roughly equally distributed around the meridian, during the allocated observing period.

The observations were carried out on the nights of 1992 April 11, 12 and 13 in the *B*, *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 pixels of dimensions 22×22 $\mu\mathrm{m}^2$: each pixel thus corresponds to 0.64×0.64 arcsec^2 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 electron per pixel, and the number of electrons per ADU was equal to 4. Bias and dark frames were taken intermittently, and flat-field exposures were taken using the twilight sky.

We monitored the objects QQ 1206+459 ($z=1.158$, $V=16.1$), 1248+401 ($z=1.03$, $V=16.3$), 1254+047 ($z=1.024$, $V=16.1$), 1338+416 ($z=1.219$, $V=16.1$) and 1352+011 ($z=1.121$, $V=16.0$) in the *V* band for periods ranging from 4–7 h; each source was observed on only a single night. The typical interval between measurements was roughly 30 min. Integration times in the *V* band were 15 min for 1206+459, 8–10 min for 1248+401, 12 min for 1254+047, 15 min for 1338+416 and 12 min for 1352+011. These exposures yielded signal-to-noise ratios for the QSOs of 50–80 on the first two nights, but the increasing sky brightness from the waxing Moon allowed signal-to-noise ratios of only about 25 to be attained on the last night of our observations. At least one frame was taken through each of the *R* and *B* passbands for all sources. Integration times were (*R*, then *B*, in minutes) (10, 15) for 1206+459, (2, 7) for 1248+401, (8, 15) for 1254+047, (10, 15) for 1338+416, and (8, 15) for 1352+011. The seeing was typically 2 arcsec.

The data were reduced with the VBO VAX 11/780 system, using the DAOPHOT software package and the COMTAL Vision image display station. Dark frames were subtracted from the image frames, and the images were flat-fielded using the sky frames in the usual manner. Photometry of the QSOs on the data frames was performed, using four concentric apertures of diameter 8, 12, 16 and 20 arcsec centred on the objects. The background was subtracted using the measured counts in annuli around the circular apertures. Because of the large seeing disc, the results presented here are based on the 16-arcsec aperture, which guaranteed the inclusion of essentially all the photons from the sources, but did not suffer from as much background and readout noise as did the 20-arcsec aperture. Three comparison stars were also reduced in a manner identical to the reduction of the QSO, with the exception of 1248+401, for which only two comparison stars were available, and one or two images of the other QSOs, in which one of the comparison stars was just out of the frame.

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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 1.

3 RESULTS

Figs 1–5 display the flux ratios determined from the observations described above. Error bars for each flux ratio point were determined by adding in quadrature the 1σ formal errors for the stellar and QSO fluxes estimated by the DAOPHOT software package. We now discuss the results for each source individually.

3.1 1206+459

This source was the only one observed on the night of 1992 April 11, so the densest temporal coverage was obtained for it, with 15 *V*-band exposures over 5.5 h. Signal-to-noise ratios of 60–80 were usually attained. The differences in colour between the QSO and stars 1, 2 and 3, respectively, are $\Delta(V-R) = -0.11$, -0.25 and $+0.02$, $\Delta(B-V) = -0.33$ and -0.40 (no good *B* value was obtained for the faint star 3). These differences in colour are small enough that any effects on the differential photometry of the convolution of the filter with the spectral differences between the QSO and the comparison stars will be negligible (e.g. Carini 1990). The relatively dark night also allowed a good ratio of signal to noise, with only flux ratios involving the faintest comparison star (3) having error bars significantly larger than the plotted symbols. There is certainly no good evidence for microvariability in this source, although at UT 16:20 there are marginally significant rises in the ratios Q/2, Q/3 and even Q/1 (note that 1/Q is plotted in Fig. 1, to keep a reasonable range in the figure), followed by a more gradual decline in these ratios over the next hour. At the same time, however, there are fluctuations in the ratios 2/3 and 1/2, so this flicker might be discounted. There are nominally statistically significant changes between the last two data points, but the faint star 3 falls too close to the chip edge and Q/1 declines while Q/2 and 2/1 rise, so the increasing airmass at large hour angles (HA= 3:16 at UT 20:49) has probably played a role in creating this discrepant situation. A final observation at UT 21:07 is not plotted, as condensation on the CCD precluded accurate measurements. To quantify these impressions, χ^2 analyses of the data were performed. These formal error estimates indicate that the probabilities of the ratios Q/1, Q/2 and Q/3 being constant are all less than 0.01; however, the probabilities of the ratios 2/1, 3/1 and 2/3 being constant are also all less than 0.02, strongly hinting that the error bars have been underestimated in this case. An increase of all the error

Table 1. Spatial separations of comparison stars from QSOs.

QSO	α(1950)	δ(1950)	Star 1		Star 2		Star3	
			Δr(″)	PA(°)	Δr(″)	PA(°)	Δr(″)	PA(°)
1206+459	12 06 26.6	+45 57 17	138	234	90	274	67	177
1248+401	12 48 26.6	+40 07 58	119	260	220	230	125	189
1254+047	12 54 27.6	+04 43 47	60	209	137	213	126	33
1338+416	13 38 52.2	+41 38 18	68	130	80	212	128	190
1352+011	13 52 25.8	+01 06 50	117	158	113	144	100	18

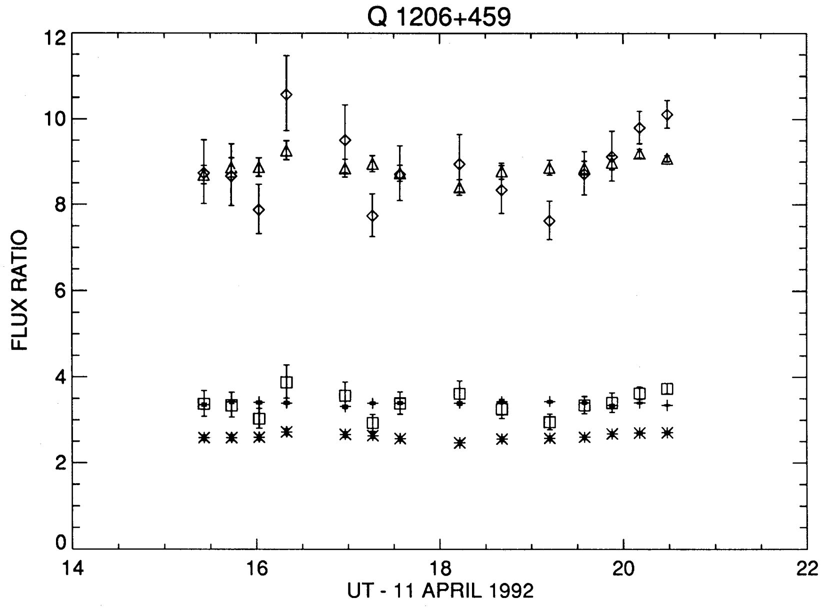

Figure 1. Flux ratios for Q1206+459 and three comparison stars, 1, 2 and 3. The symbols correspond to the following ratios: 1/Q (+); Q/2 (∗); Q/3 (◇); 1/2 (△); and 2/3 (□). Note that the error bars are often significantly smaller than the size of the symbols. Also note that at some times the + symbols (and their associated tiny errors) lie within the □ symbols in this figure.

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bars by 50 per cent reduces the χ^2 values to insignificant (<0.15) levels.

3.2 1248 + 401

One of two sources observed on 1992 April 12, the temporal coverage is good, with eight measurements in V over 5 h; a signal-to-noise ratio of ~ 50 was achieved for most measurements. A ninth (unplotted) measurement, at UT 21:11, was corrupted by condensation on the CCD. Unfortunately, there were only two reasonable comparison stars in the field. The differences in colour between the QSO and stars 1 and 2, respectively, are $\Delta(V-R) = -0.20$ and -0.24, $\Delta(B-V) = -0.17$ and -0.14, so again the colour differences should not affect our results. There is no hint of variability (Fig. 2), with the formal error bars implying insignificant variations [$P(\chi^2_\nu) < 0.50$].

3.3 1254 + 047

Because of the brighter sky conditions on the last night (1992 April 13), signal-to-noise ratios of only 25 were typical, so the uncertainties in the measurements are greater. Only seven frames in V were taken over 5 h, and star 2 was just outside the frame for two crucial images at UT 15:56 and 16:46. The differences in colour were again moderate, with

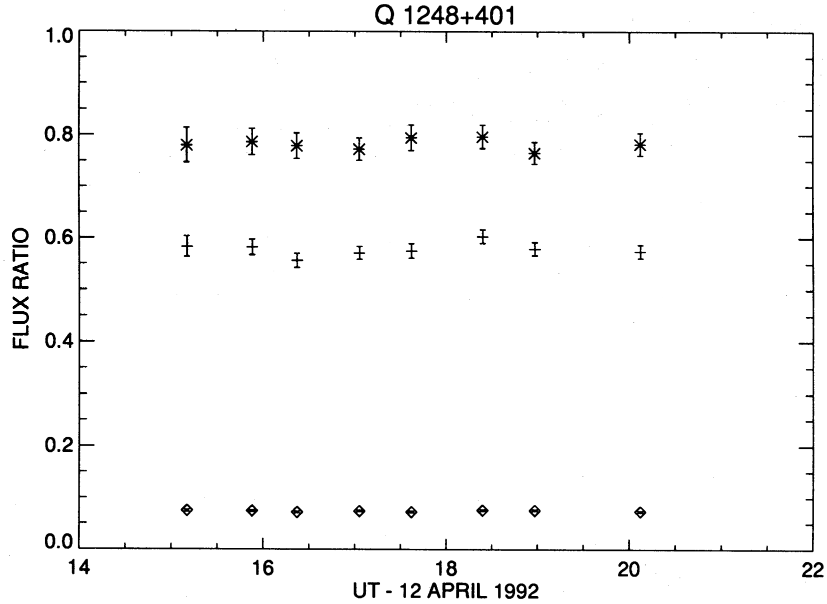

Figure 2. Flux ratios for Q1248 + 401 and two comparison stars, 1 and 2. To keep all quantities on the same scale, 10 × the ratio Q/1 is plotted as + signs, while the unscaled values of Q/2 appear as $*$, and values of 2/1 are shown by ◇.

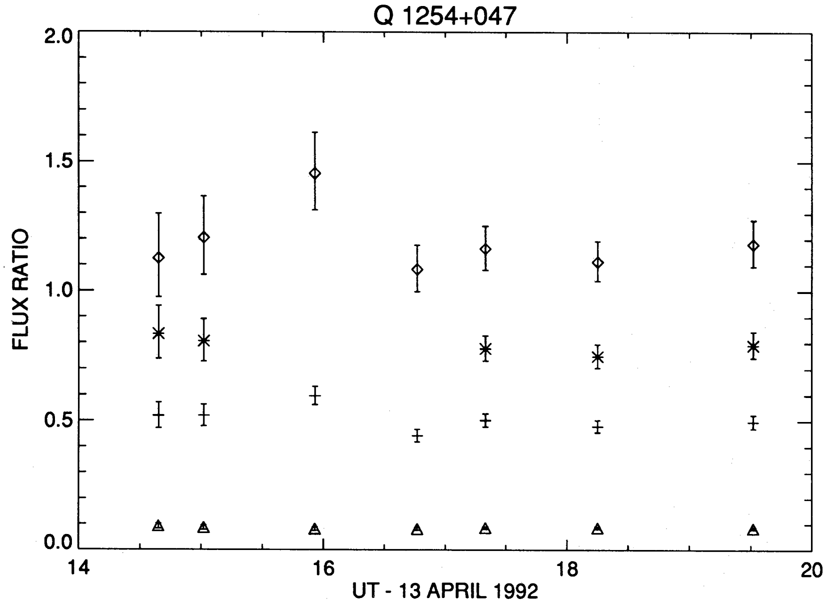

Figure 3. Flux ratios for Q1254 + 047 and three comparison stars, 1, 2 and 4. As in Fig. 2, the symbols are as follows: 5 × Q/1 (+); Q/2 ($*$); Q/4 (◇); and 4/1 (△).

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those between the QSO and stars 1, 2 and 4, respectively, being $\Delta(B-V)=-0.26$, -0.21 and -0.24, while the sky was too bright at the time the R measurement was made to allow reliable values to be obtained. As is clear from Fig. 3, both Q/1 and Q/4 appear to rise from UT 15:02 to 15:56 by about 20–25 per cent, and drop quickly to a value at or below the original level by UT 16:46, while the ratio 4/1 drops by about 5 per cent in the first interval but remains at that level over the second interval. Taking the formal error estimates, the χ^2 probability that Q/1 is constant is less than 0.03, while the larger error bars for star 4 give only a 50 per cent formal probability of variation for Q/4; the ratios 1/4, 2/1 and 2/4 are all very steady (probabilities of constancy >0.96); most unfortunately, the flux of star 2 was not measurable for precisely the time when the variability in Q/1 seems to have occurred, so we cannot claim a positive detection of microvariability.

3.4 1338+416

The second source observed on the second night, it also had a typical signal-to-noise ratio of about 50. Eight measurements in V were made over 6 h, but, as for 1248+401, the last measurement (at UT 21:26) was corrupted by condensation and is not plotted. The differences in colour between the QSO and stars 1, 2 and 3, respectively, are $\Delta(V-R)=-0.10$, -0.05 and -0.54, $\Delta(B-V)=-0.40$ and -0.25 (with no good B value obtained for star 3); while star 3 is far enough away in colour to pose some problems, the other two are close enough to be reasonable comparators. Yet again, as shown in Fig. 4, no significant fluctuations are seen; there may be a small rise in the QSO flux at UT 16:06, followed by a return to the previous level. (Note that, while Q/1 shows the rise directly, we have plotted 2/Q and 3/Q to keep all ratios less than 1, so the plotted dips actually correspond to apparent rises in QSO flux at UT 16:06). The χ^2 analysis yields probabilities not exceeding 0.77 of quasar variations, and the stellar ratios produce probabilities of variation at similar low levels of significance.

3.5 1352+011

For this second source observed on the bright final night, the signal-to-noise ratio was only around 25, and only five exposures were taken in the V band over the course of around 4 h, so this is the lowest quality data set taken. All three stars were on the frame for all but UT 16:14, when the faint star 3 was not measured. The differences in colour between the QSO and stars 1, 2 and 3, respectively, are $\Delta(V-R)=-0.23$, -0.23 and -0.61, $\Delta(B-V)=-0.29$, -0.02 and -0.54. Star 3 is distant in colour, but the other two brighter stars are close enough to prevent large errors induced by different responses to the filter. The ratios Q/1 and Q/3, displayed in Fig. 5, show evidence of declines by around 20 and 30 per cent respectively between UT 15:35 and 18:35, and these ratios are then essentially constant until UT 19:49. While the χ^2 values based on the formal error estimates yield probabilities of constancy for Q/1, Q/2 and Q/3 of <0.0004, the chances of constancy in the ratios 2/1 and 2/3 are both less than 0.02, while 3/1 has $P<0.17$. This again implies that the error bars have probably been underestimated (and/or that star 2 varied during this interval); an increase of each error bar by 50 per cent yields probabilities of constancy for Q/1, Q/2 and Q/3 of between 0.04 and 0.06, while those for 2/1, 3/1 and 2/3 range from 0.20 to 0.51. Thus there is a real hint of change in this RQQSO but, as the measurement is only at the $\sim 2\sigma$ level, we cannot positively claim to have detected intra-night optical variability.

4 DISCUSSION AND CONCLUSIONS

We have begun a search for optical microvariability in radio-quiet but optically bright and luminous ($M_V \ll -23$) quasi-stellar objects. The five such objects reported here are

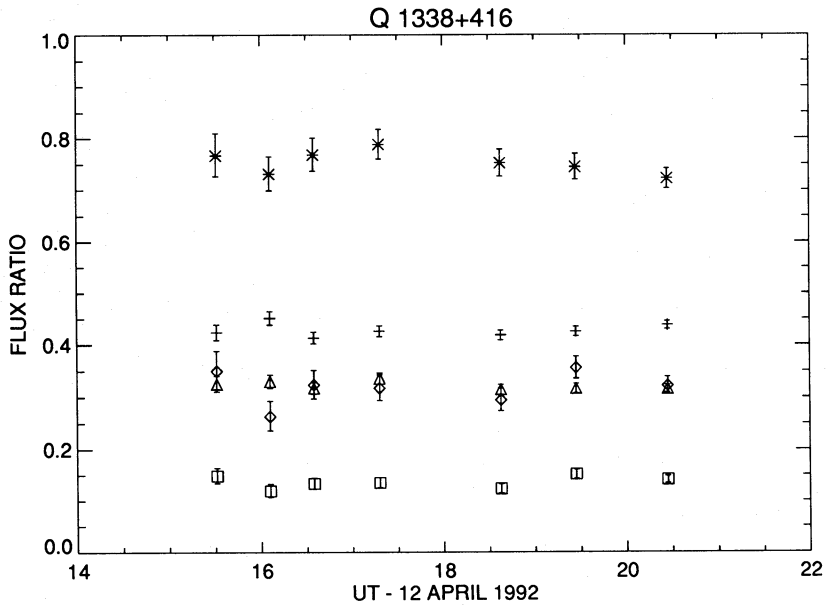

Figure 4. Flux ratios for Q1338+416 and three comparison stars, 1, 2 and 3. Symbols are as follows: Q/1 (+); 2/Q (*); 3/Q (◇); 2/1 (△); and 3/1 (□).

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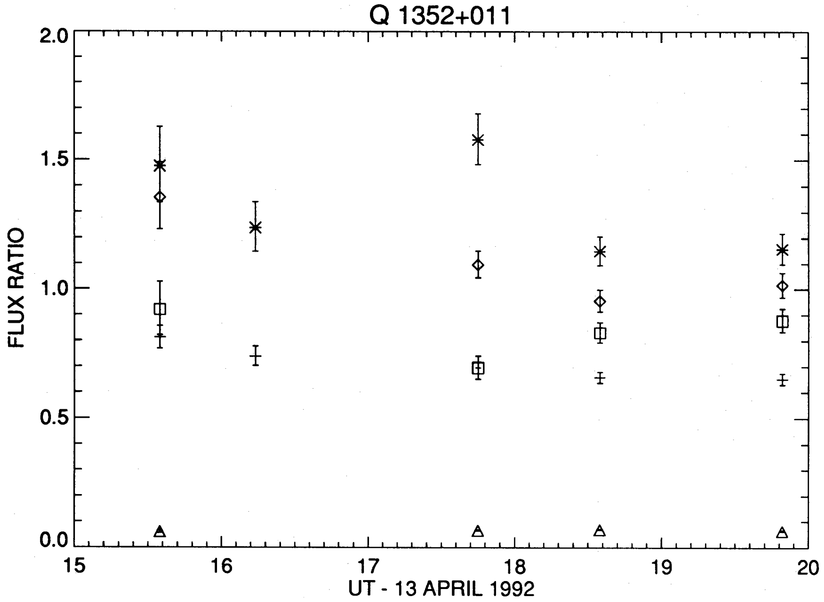

Figure 5. Flux ratios for Q1352 + 011 and three comparison stars, 1, 2 and 3. Symbols are as follows: 10 × Q/1 (+); 2/Q (∗); Q/3 (◇); 3/1 (△); and 2/3 (□).

among the prime candidates for testing the hypothesis that the origin of microvariability is related to accretion disc fluctuations. While on a few occasions there are hints of intra-night variations, no strong claim can yet be made that we have really observed intra-night variability in any of these five RQQSOs.

If small but significant intra-night flux variations are clearly found in radio-quiet quasars, we will no longer be able convincingly to invoke jet-based intrinsic or extrinsic models. On the other hand, if a thorough search turns out to be negative, then the accretion disc models would be disfavoured. In our limited data set, no such fast flux changes were *clearly* established down to the 2–5 per cent level, depending on the source. It should be recalled, however, that even blazars that are definitely microvariable do not show this behaviour during every observing run (e.g. Carini 1990). The observations presented here, and in an earlier paper (Gopal-Krishna et al. 1993), are the first of their kind for this class of object. They obviously need to be repeated in a more intensive fashion for individual objects, and extended to a larger sample of RQQSOs in order to arrive at a clear answer to the question of whether optical microvariability is exhibited by this class of object. This information could lead to firm conclusions about the underlying physical mechanisms for microvariability, or could at least tightly constrain some of the prominent theoretical explanations.

In evaluating theoretical models for microvariability, we note that most models for AGN invoke accretion discs. Since such discs are known to be subject to numerous instabilities (e.g. Rees 1984), it is reasonable to expect these instabilities to be reflected in changes in the AGN luminosity. 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 regions 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 (Chakrabarti & Wiita 1992). Thus UV and optical fluctuations could potentially arise from such discs. In just one case, however, the blazar 0716 + 714, the characteristic time-scales for optical and radio variability appear to change simultaneously from about a day to about a week (Quirrenbach et al. 1991); to explain this within the accretion disc picture would require coherent processes, probably operating within flares in disc coronae (e.g. Lesch & Pohl 1992; Krishan & Wiita 1993). Such a tight multiband correlation, if confirmed, is also unexpected from conventional shock-in-jet models. Jet/shock models would also be disfavoured if the level of microvariability were 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, in preparation).

Even the hints of microvariability that we have found in some of these RQQSOs are quite exciting, and demand that additional observations of these sources and others like them be carried out.

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