Rapid Optical Variability in Radio-Quiet Quasars

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Rapid Optical Variability in Radio-Quiet Quasars

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Abstract

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Rapid Optical Variability in Radio-Quiet Quasars

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A Thesis presented to the National Council of Education Authority for the degree of M.Sc.

August 1999
Abstract

Results from imaging and spectral surveys at radio wavelengths indicate that radio quiet quasars (RQQs) may have accretion-fuelled Super Massive Black Holes (SMBH) as their so-called central engines, similar to those hypothesised for radio loud quasars (RLQs). Recent evidence suggests that some RQQs may also harbour weak jets. Rapid optical variability is a common property of most RLQs with compact radio cores, flat radio spectra, and extended linear features emanating from the core and is linked to the presence of a powerful relativistically boosted jet. We present the results of a 3 year monitoring campaign of sixteen RQQs displaying evidence of compact cores and flat or inverted radio spectra. The objective of the campaign is to search for rapid optical variability. The observations were carried out mainly in the V-band for most of the sample. PG 1634+706 and E1821+643 have been observed extensively in V, R, and B bands. Differential photometry is carried out using IRAF routines to calculate instrumental magnitudes. For differential photometry all of the suitable reference stars available on the CCD frame containing the RQQ are used. This is a novel approach which we believe leads to the best estimate of the quasar lightcurve.

We find that in most cases the photometric accuracy attainable lies between \( \approx 40-50 \) millimag, based on the analysis of the scatter in the reference stars. This provides the most accurate (though conservative) estimate of the uncertainty in our observations. We also find that the errors calculated by IRAF routines are underestimated at least by a factor of 1.5. We also point out that instrumental effects can lead to spurious variability of \( \approx 50-80 \) millimag at these short timescales.

We find no evidence for variability within a given night for any of our sources. We find evidence of marginal variability from night-to-night in PG0003+199 of \( \approx 30 \) millimag. We find that the lack of observed ROV in our RQQ sample doesn't necessarily imply the lack of a weak jet but that the contrast effects in the optical (where the flux is dominated largely by the luminous accretion disk in RQQs) may prevent us from detecting rapid variations that may arise in a weak jet given the limit of the photometric accuracy attained.
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Chapter 1

Introduction

The objects studied for this thesis form part of a large group of objects known as Active Galactic Nuclei, or AGN. In general the term AGN refers to the existence of energetic and sometimes extremely violent phenomena in the nuclei, or central regions, of galaxies which can not be attributed to stars. The first hint of the violent heritage of galaxies was found by Edward A. Fath, who in 1908 was observing the spectra of spiral nebulae. Although most displayed an absorption-line spectrum produced by the combined light from all the galaxy's stars, NGC 1068 displayed six bright emission lines. In 1926 Edwin Hubble recorded the emission lines of this and two other galaxies. In 1943, Garl K. Seyfert reported that a small percentage of galaxies have bright nuclei that are the source of broad emission lines produced by atoms in a wide range of ionisation states. Today, these galaxies are known as Seyfert galaxies.

In the 1960s astronomers also began to discover unusual "stellar like" objects with very large redshifts. These redshifts indicated that these objects were extremely far away from the Earth according to the Hubble law. Therefore, to be observed from Earth these objects must be very luminous, typically about 100 times brighter than an ordinary galaxy. Some of these objects were found to exhibit features such as jets that propel matter outward at relativistic speeds and many were found to show variability in their brightness. At the time, these objects were named quasi-stellar radio sources (which was shortened to quasars) or QSOs since "ordinary" stars are not strong sources of radio emission. It is considered well-established that these radio sources originate in an accretion-fuelled central engine, and a super massive black hole (SMBH) is generally accepted as the central engine.
Together Seyferts and quasars form the two largest subgroups of AGN. The fundamental distinction between them is the amount of radiation emitted by the compact central source; for a typical Seyfert galaxy the total energy emitted by the nuclear source at visible wavelengths \( \approx 10^{31} L_\odot \) (this is comparable to the energy emitted by all the stars in the galaxy), but in a typical quasar the nuclear source is brighter than the stars by a factor of 100 or more.

1.0.1 Basic properties of AGN

The basic properties of AGN as defined in the late 1960s by Sch (Schmidt 1969) are as follows:

a) Star-like objects identified with radio sources.
b) Time-variable continuum flux.
c) Large UV flux.
d) Broad emission lines.
e) Large redshifts.

Not all the objects classified as AGN today share all of these properties. One of the defining characteristics of AGN is their very broad energy distribution, or SED. AGN are among the most luminous sources in the sky at every wavelength of the electromagnetic spectrum. Figur... shows a sketch of the continuum observed for many types of AGN. Its notable feature is its persistence over some 10 orders of magnitude in frequency. This wide spectrum is different from the thermal (blackbody) spectrum of a star, or a spectrum produced by the summation of large numbers of star spectra, and therefore cannot be described in terms of blackbody emission at a single temperature, or as a summation over a small range in temperature. So, a power law is used to describe the broad-band SED of a quasar's continuum:

\[ F_\nu = C \nu^{-\alpha} \]

where \( F_\nu \) is the specific flux (i.e. per unit frequency interval), \( C \) constant and \( \alpha \) is the spectral index. It was thought that the quasar spectra were quite flat and hence \( \alpha \) was believed to have a value of \( \alpha \approx 1 \approx 0 \) on a conventional plot of specific flux versus frequency has equal \( \nu \) per unit frequency interval. Fits to quasar spectra over large frequency ranges yield different values for \( \alpha \) for different spectral ranges. The power red within
Figure 1.1: A sketch of the continuum observed iAGN.
any frequency range $\nu_1$ and $\nu_2$ is given by

$$P(\nu_1, \nu_2) \propto \int_{\nu_1}^{\nu_2} F_\nu d\nu = \int_{\nu_1}^{\nu_2} \nu F_\nu d\nu / \nu \log \int_{\nu_1}^{\nu_2} \nu F_\nu d\log \nu \quad (1.2)$$

so that equal areas under a graph of $\nu F_\nu$ against $\log \nu$ correspond to equal amounts of energy. Thus a value of $\alpha \approx 1$ reflects the horizontal trend seen to the right of the turnover in figure 1.1. Sometimes the minus sign in equation 1.1 is absorbed into the definition of the $\alpha$ amplitude $\alpha$ is defined with the opposite sign. Also, specific fluxes in the UV to optical are often measured per unit wavelength interval rather than per frequency interval. In that case equation 1.1 is transformed to an equivalent form:

$$F_\lambda = C' \lambda^{\alpha - 2} \quad (1.3)$$

Although the continuous spectra of AGN are well known to be more complicated, figure 1.1 still serves as a good approximation. The spectral index typically has a value between 0.5 and 2 that generally increases with increasing frequency. The value of $\alpha$ is only constant over a limited range of frequencies, such as IR and optical. The shape and the polarization of the optical-UV spectrum indicates that it can sometimes be separated into contributions from thermal sources (blackbody spectrum, low polarization) and non-thermal sources (power-law spectrum, significant polarization). The thermal component is classically known as the *bump* and is marked in figure 1.1.

A pure power law spectrum is the signature of synchrotron radiation involving relativistic electrons and magnetic fields. A synchrotron spectrum is produced by the combined radiation emitted by the individual electrons as they spiral around magnetic field lines. If the distribution of the individual electrons obeys a power law, then the resulting synchrotron spectrum is described by equation 1.1. However, the synchrotron spectrum does not continue to rise without limit as the frequency decreases. At a transition frequency, the spectrum turns and varies as $\nu$. This occurs because the plasma of the spiralling electrons becomes opaque to its own synchrotron radiation. This effect is known as *synchrotron f-absorption*.

### 1.0.2 Radio properties of AGN

The radio morphologies of AGN are usually decribed broadly in terms of two components, *extended* (spatially resolved) and *compact* (unresolved at $\approx 1''$
resolution). Although these have different spectral characteristics, the signature of the synchrotron mechanism seems to be present in both types. The extended-component morphology is usually double, i.e., two lobes of radio emission located nearly symmetrically on either side of the optical quasar or galactic centre. The linear extent of these extended features can be as large as megaparsecs and the position of the optical AGN is usually coincident with that of a compact radio source. The main difference between the two types is that the extended component is optically thin to its own synchrotron emission at radio frequencies, whereas this is not the case for the compact components.

Extended radio structures are divided into two separate luminosity classes (Fanaroff and Riley 1974):

(i) Class one known as FR I objects, are weak radio sources which are brightest at the centre with the surface brightness decreasing towards the edges;

(ii) Class two known as FR II objects that are limb-brightened, and sometimes show enhanced emission at the edge of the radio structures. $L_v(1.4 \text{GHz}) = 10^{32} \text{ergs s}^{-1} \text{Hz}^{-1}$ is generally accepted as the transition specific luminosity between the two types (Bridle and Perley, 1984).

Very long-baseline interferometry (VLBI) surveys yield upper limits typically of $\approx 0.01 \text{pc}$ for the core. The radio spectra of compact sources are usually flat, with $\alpha \leq 0.5$, if a power law is assumed. Different parts of the compact region become optically thick at different frequencies, and this can flatten out the integrated spectrum over quite a broad range.

In addition to the compact and the extended components, radio objects are also observed to house jets which are extended linear structures that seem to originate at the compact source or the core and stretch out to the extended lobes. In radio maps at milliarcsecond (mas) resolution, these jets seem to show structures that look like bends and knots. The appearance of jets suggests that they transport energy and particles from the core out to the lobes. The extended, compact and jet components have different spectral shape. The relative strengths also vary considerably from source to source, with the lobe-dominated having predominantly steep spectra and the core-dominated having flat spectra. The lobes are expected largely to radiate isotropically whereas the compact-core and jet components probably emit anisotropically.
1.1 Classification of Quasars

Since the discovery of quasars it has been known that the some have strong radio emission and others do not. Classically, quasars are broadly divided into two main groups based on their radio emission: radio loud quasars (RLQs) and radio quiet quasars (RQQs). In the RLQ population the ratio, $R$, of radio to optical emission is greater than about ten; and in the RQQ population $R$ is less than ten (Kellerman and Sramek 1989). Alternatively, the separation between RLQs and RQQs may be defined by their radio luminosity. Sources with a 5GHz radio luminosity greater than $10^{25}$ W/Hz ($H_0 = 50$ km/sec/Mpc, $q_0 = 1/2$) are usually referred to as RLQs and the ones with luminosity less than $10^{24}$ W/Hz as RQQs. Falcke et. al (1996) reported that for the PG quasar sample the RQQs tend to cluster around $R = 0.2$, while RLQs tend to cluster around $R = 300$ and there are quite a few sources in between the distributions, where RQQs and RLQs blend into each other. The classification of a quasar as RLQ or RQQ is somewhat ambiguous in the range $R = 10 - 50$. Flack et al. (1996) called these radio intermediate quasars, or RIQs.

Many RLQs exhibit the double, often collinear radio morphology as outlined in section 1.02 (comprising of compact cores and lobes of extended emission fed by jets) where as radio images of majority of RQQs often just show a weak radio component coincident with the optical quasar nucleus, which is in some cases resolved (Miller et al., 1993). The RLQ population may be further divided using an orientation based unification scheme and the radio spectral properties (Gopal-Krishna et al., 1995). RLQs, which include BL Lacertae objects (BL Lacs), Optically Violently Variables (OVVs) and Radio Galaxies show evidence of relativistic jets emerging from the very core of the galaxy. This relativistic jet is also one of the keys to the unification scheme for RLQs. According to this scheme, radio galaxies, lobe-dominated quasars and core-dominated quasars are one and the same type of object, but seen under different aspect angles (Urry and Padovani 1995). Lower powered, edge darkened (FR I) radio galaxies, if observed with the jets pointing nearly towards us, would appear as BL Lacs. Relativistic boosting leads to an appearance of a core-dominated quasar, where the core is much brighter than the lobes. Higher powered objects whose jets make an angle $> 40^\circ$ to our line of sight are observed as ordinary edge brightened radio galaxies (FR II). Those with approaching jets between $\sim 10^\circ$ and $\sim 40^\circ$ to our line of sight are seen as radio loud QSOs. Finally, the luminous sources with jets
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that make an angle of $< 10^\circ$ to our line of sight are named OVVs and Highly Polarised Quasars (HPQs). The radio spectral index can be used to separate core-dominated quasars ($\alpha \geq 0.5$) from the lobe-dominated ($\alpha \leq 0.5$) (Kellerman and Sramek 1989).

However, Falcke et al. (1996) point out that if $R \geq 10$ is used as the definition for RLQs, severe inconsistencies are found in the content of the PG quasar sample with this simple unified scheme which suggests that the flat-spectrum core-dominated objects are the boosted counterparts to the lobe-dominated steep-spectrum RLQs as mentioned above. According to the unified scheme, therefore, flat-spectrum core-dominated objects should be rare and have higher fluxes and R values compared to steep spectrum sources. However, if treated as a single population, the flat-spectrum objects are quite frequent (40%) in the PG sample, and the majority have fluxes and R values lower than steep spectrum objects. Therefore using this single population hypothesis would exclude the possibility that core-dominated quasars are generally the boosted counterparts to lobe-dominated steep spectrum RLQs.

They suggest that the problem can be rectified if one assumes that the distributions of flat and steep spectrum quasars are bimodal. Here, one would separate RLQs and RQQs with steep spectra at $R \approx 25$, and RLQs and RQQs with flat spectra at a much higher value of $R \approx 250$, although the latter $R$ value is fairly uncertain due to the small number of flat spectrum sources. As a result, the fraction of the flat spectrum quasars would be only $\approx 10\%$ for both RLQs and RQQs (Falcke et al., 1996). The important implication of this suggestion is that some RQQs are as much subject to relativistic boosting as are RLQs.

1.2 Powerhouses Of RLQs versus RQQs

The fundamental question about AGN is how the energy that is detected as radiation is generated. An AGN can outshine a galaxy by as much as a 1000 times and yet the emission seems to arise from a volume significantly smaller than a cubic parsec. The current working model for AGN phenomena is a central engine that consists of a hot accretion disk surrounding a SMBH. Energy is produced by gravitational infall of matter which is heated to high temperatures in a dissipatative accretion disk. The underlying physical arguments for this view have been around since Zel'dovich and Nikov (1964).
Indeed, there is compelling evidence (like the observation of superluminal motion and other indicators of bulk high Lorentz factors such as high brightness temperatures, rapid variability and evidence from radio imaging) for an accretion-fuelled, relativistic jet producing SMBH model as the central engine responsible for the tremendously luminous and rapidly variable emissions detected in RLQS (Begelman, Blandford, and Rees 1984). Also, the existence of accretion disks around SMBHs has been more convincing since the discovery of masers in the core of NGC 4258 (Miyoshi et al. 1995). Other strong evidence for disks comes from the presence of a quasi-thermal "big blue bump" in the spectra of many quasars (Kellerman and Sramek 1989), although it has been argued that this effect could be due to free-free emission (Barvainis et al. 1993).

How does the nature of the emission mechanisms in RQQs compare with RLQs considering that the total radio luminosity for RQQs is generally two or three orders of magnitude lower than that of a typical RLQ, with similar ratios in many other wavebands (Miller, Rawlings, and Saunders 1993). It has been proposed that the activity in RQQs may be explained by a circum-nuclear starburst model, i.e. strongly radiative supernovae and supernova remnants (SNRs) in a very dense environment (Terelvich et al., 1992). Sopp and Alexander (1991) argued this on the basis of the striking continuity between the far Infrared-radio correlation of RQQs and that of star-forming galaxies, ultraluminous infrared galaxies and Seyferts. This is offset from the same correlation between radio galaxies and RLQs. The peak luminosity at $5GHz$ of the most powerful supernova known (1986J; Rupen et al., 1987) is $\approx 10^{26} WHz^{-1} sr^{-1}$. Therefore, between $\approx 100 - 1000$ supernovae at peak luminosity would be required to power a single RQQ (as typically, radio luminosity for RQQs at $5GHz$ is $\approx 10^{22}/10^{23} WHz^{-1} sr^{-1}$). For the most luminous RQQ in our sample (PG 1222+229 with $L_{5GHz} = 2.0 \times 10^{26} WHz^{-1} sr^{-1}$), it would require a phenomenal $10^6$ supernovae at peak luminosity. This implies a very sustained supernova rate with an unprecedented supernova space density (Blundell and Beasley, 1998) since the values for the size of the emitting region yield volumes that are between $10^5$ and $10^7$ times smaller than those predicted by Terelvich and Boyle (1993) and observed in the M82 starburst galaxy (Muxlow et al. 1994). This model also does not account for x-ray variability seen in some RQQs.

An alternative suggestion is (Miller et. al 1993) that the radio emission originates from weak radio jets arising from the AGN in a scaled down version of the mechanism present in RLQs. The evidence for this suggestion
is gathering momentum. Blundell and Beasley (1998) carried out a VLBA imaging survey of 12 RQQs and found strong evidence for jet producing central engines for 8 RQQs in their sample. They detected high brightness temperatures in the order of $\approx 10^7$ and $10^8 K$ which are $\approx 2$ to 4 orders of magnitude higher than those predicted for typical SNR events (Muxlow et al., 1994) and are more in line with brightness temperatures observed for RLQs. They also observed structures indicative of jets in RQQs PG 1216+069, PG 1222+225, PG 1351+640 and PG 1407+265, but they do point out that due to low brightness levels and short snapshot type observations used for their sample, it is difficult to determine the reality of these features.

VLA observations of a number of RQQs (Kellerman et al., 1994) also revealed signs of weak, bi-polar radio structures. Falcke et al. (1997) took a long integration VLA map of Mrk 34 which is classified as a Seyfert 2 galaxy but has an [O III] luminosity that is typical for a RQQ with an optical+UV luminosity of several $10^{45} \text{erg s}^{-1}$. This long integration revealed an amazing jet structure in this galaxy.

Barvainis et al. (1996) measured centimeter-wavelength radio spectra for 32 radio quiets and 7 luminous Seyferts. They found a variety of shapes, from straight and steep spectra, to flat or inverted and strongly curved spectra. They found that the relative frequencies of the different shapes are similar to those found in RLQs. Based on a larger sample, (including sources from Antonucci and Barvainis 1988) they found that about 40% of RQQs in their sample appeared to have flat or inverted spectral components, closely related to the flat spectrum synchrotron cores seen in RLQs.

1.3 Variability

The fact that quasars are variable has been known since shortly after their discovery in the 1960s. Quasars are variable in every waveband in which they have been studied, not only in the continuum but also in the broad emission lines. Optical continuum variability of quasars was established even before the emission-line redshifts were understood (e.g. Matthews and Sandage 1963). Many RLQs were found to be variable at the 0.3 – 0.5 mag level over timescales of few months. Variability from radio to x-ray wavelengths is a very important property of AGN because it provides a simple but effective method for probing the nature of the so-called central engine for AGN.

In the last few years, with improved instrumentation and improved signal-
to-noise ratios, astronomers have been able to examine AGN for small brightness fluctuations on timescales of a day or even a few hours. Many RLQs, particularly blazars show significant \textit{Intraday variability}, or IDV in the centimetre radio band (e.g. Quirrenbach et al., 1989; Krichbaum, Quirrenbach and Witzel (1992); Quirrenbach et al., 1992). IDV at x-ray wavelengths have also been established (Snyder et al., 1980).

IDV in the optical was clearly established by using CCD cameras as N-star photometers (Miller et al., 1992). \textit{Rapid optical variability} (ROV), found for most blazars is $\sim 0.01 \text{ mag hr}^{-1}$ (Wiita, Gupta, Chakarbarti et al., 1992). As shown by Carini et al.(1991) for a sample of 20 blazars, if such a source is investigated for over 8 hours the probability of observing significant ROV exceeds 80%, and nearly all the objects classified as blazars exhibit detectable fluctuations on a night to night basis. A study of 34 BL Lacs by Heidt and Wagner (1995) detected ROV in 28 (82%); and 75% of these variable BL Lacs changed significantly in less than 6 hours, confirming the high frequency of ROV for blazars.

Currently it is accepted that not only blazars, but many RLQs present microvariations that is fluctuations at 1-2 \%, on timescales of few hours to days in the optical wavebands (Wagner and Witzel 1995). So, what can be said about RQQ variability properties compared to RLQs. Although it has been strongly suggested that RQQs show small amplitude variations in the optical at timescales of years (Giveon et al., 1999), but whether RQQs show ROV is still an enigma. Part of the reason for this has been the lack of monitoring up until the early 1990s. Gopal-Krishna et al. 1995, 1993a, 1993b were the first to study RQQs for optical IDV and reported only marginal evidence any such variations in RQQs. Another monitoring campaign of RQQs and RLQs found that only 3 out 19 RQQs showed detectable ROV compared to 9 out 11 RLQs (Jang and Miller 1995, 1997). De Diego et al. (1998) conducted a comparison study of ROV properties in a sample of 17 RQQs and 17 core-dominated, or CRLQs. They observed pairs of RQQs and RLQs matched in brightness and redshift using the same equipment and on the same night. They found that the occurrence of ROV events was not significantly different in the RQQs and the CRLQs. But we found that their data is not particularly convincing of this conclusion as some of the comparisons used also show rapid fluctuations as well as the objects, albeit, not at the same time. Rabbette et al. investigated 23 RQQs with very high luminosities ($-27 \leq M_v \leq -30$) and found no evidence of ROV in their sample, however PG 2112+059 was detected to have varied by 0.18 mag over
a period of four years.

So, at present the evidence for ROV in RQQs is little tentative; because there have only been a handful of research efforts, no separate study has ever reproduced the same result and no single RQQ has been observed to show ROV in different studies. Therefore, the question posed above, how does RQQ variability (especially in terms of ROV) compare with that observed in RLQs remains largely unanswered.

1.3.1 Models to explain Rapid Optical Variability

Theoretical explanations for ROV can be divided into extrinsic and intrinsic types. One extrinsic explanation is refractive interstellar scintillation, or RISS, but this is only relevant at radio frequencies. Density inhomogeneities of electrons of the interstellar medium (ISM) on different spatial scales introduce diffractive and refractive scattering, resulting in the angular broadening of compact sources and apparent variability in all AGN (Rickett 1990). While a statistical analysis of radio fluctuations of an entire sample of compact flat spectrum sources is consistent with RISS always being present (Quirrenbach et al., 1992), this mechanism is unable to account for the observed simultaneity and similar amplitude of variations over a large range of radio frequencies (Qian et al., 1991; Quirrenbach et al., 1992). The close correlations between radio and optical variations observed in some sources also rule out the possibility that all rapid radio variations are due to RISS (Wagner et al. 1995) (as RISS cannot produce fluctuations at optical wavelengths).

Transient microlensing effects (Chang and Refsdal (1979); Surdej et al., 1993b; Jaunsen et al., 1995) produced by compact bodies in an intervening galaxy or in the host galaxy of the quasar, causing the enhancement of quasar brightness, has been proposed as another extrinsic mechanism for IDV. However its statistical likelihood at present is not clear (Gopal-Krishna et al., 1995), but it can explain many of the features of rapid variations at different wavelengths. Hawkins (1993) has argued that microlensing by a cosmologically significant population of sub-stellar objects is a plausible explanation to account for the majority of the multiyear optical variations recorded (e.g. Smith, Leacock and Webb 1988).

Among intrinsic explanations there are currently two main models that attempt to explain ROV. One model is based upon relativistic jets and hypotheses that a relativistic shock propagates down the jet and interacts with irregularities in the flow (Marscher, 1992) causing these brightness fluctua-
tions. This model has long been dominant in attempts to explain BL Lacs. Other models based on the accretion disk scenario, deem numerous flares or hotspots on the surface of the accretion disk (Wiita et al., 1993) and various plasma processes (Krishan et al., 1994) responsible for these variations. These accretion disk models do not allow for large amplitude variability, though microvariability on short timescales or larger-amplitude variability on longer timescales is possible. These models are discussed in greater detail in sections 1.4 and 1.5.

1.4 Accretion disk based models

1.4.1 Flare models

Phenomenological models for flares randomly emerging at different locations and different times on the accretion disks (Wiita et al., 1991) are particularly relevant for variations in the optical and UV bands. Standard thin accretion disks are susceptible to breaking up into rings (Lightman 1974) as viscosity generates more energy than can be removed by radiation transport. This, and other possible magnetic and thermal instabilities may increase enough to create regions of high density and high temperature, causing non-axisymmetric "hot spots" on the disk. Specific examples of causes of such asymmetries are: weak spiral shocks produced by gravitational perturbations (Wiita, Mangalam, Chakarbarti, 1992a); magnetic instabilities present on the disk or in the thin corona above it (Shibata et al., 1990) and hydrodynamical vortices (Abramowicz et al., 1992).

The most detailed phenomenological models applied to the optical and UV were presented by Mangalam and Witta (1993). The components contributing to variability in their models are:

(1) Eclipsing of hot spot by parts of the disk between that individual spot and the observer. There often exists a range of azimuthal positions at a given radius within which the spot is eclipsed, and this is directly dependent on the observer's viewing angle and the disk geometry.

(2) Gravitation and rotation induced (Doppler) frequency shifts which vary with the spot location and viewing angle.

(3) Time delays due to differences in path length to the detector; this also varies with the spot coordinates.

(4) Intrinsic variability is phenomenologically modelled via spot lifetimes
and spot luminosities. If, as expected, most active AGN are viewed close to face-on, then this intrinsic variability will dominate the rotational modulations.

The disk shape influences all aspects of variability, most noticeably for component (1) mentioned above. It is expected that eclipsing would influence variability much more in thicker disks and at larger inclinations. In both of these cases the applicability of this model is weaker as effects of gravitational lensing have not been included (Mangalam and Wiita, 1993).

1.4.2 Spiral shocks in accretion disks

Studies of accretion disks associated with binary stars show that external gravitational perturbations cause spiral waves that can steepen into shocks. Such shocks can be quite efficient in transporting angular momentum (Swada et al., 1986). These shocks, producing regions of higher density and temperature, would naturally cause the perturbed accretion disk to emit more radiation than a steady-state disk.

These shocks break up and reform, producing "hot spots" on the disk surface yielding variations in luminosity. The simulations of these spiral shocks carried out by Witta and his co-workers showed that typically, the perturbations grow quickly for approximately half of the orbital period of the perturbing mass, producing increases in luminosity which can be identified as flares. Subsequently, a quasi-steady state, with overlapping fluctuations on the order of 5% – 10%, has been established. The time-scales of these fluctuations can agree with those of microvariability if $M_{\text{SMBH}} < 10^8 M_\odot$ and the perturber enters to within a few hundred $R_{\text{SMBH}}$ where $M_{\text{SMBH}}$ is the mass of the supermassive blackhole and $R_{\text{SMBH}}$ is the radius.

Different angular momentum distributions lead to different perturbed structures. To begin with, Keplerian simulations show at first one, and later two well defined spiral structures. These spiral features are analogous to those seen in binary star disk models, where the perturber is completely outside the disk; however, in this case, the spiral structures can continue outside the orbit of the perturber. Simulations with constant angular momentum produce more violent disks and with the dissipation of angular momentum, spiral shock structure emerges. In most cases, quasi-stable, denser and hotter blobs (supported by pressure gradient and Coriolis forces) appear. These hot-spots form in the inner parts of the disk and slowly propagate outwards before dissipating. These live substantially longer than one local orbital
period, $P(r)$, in the inner parts of the disk. In the outer regions, where the Keplerian periods are longer, the blobs usually live $< P(r)$. These differences are consistent with the different behaviour seen in the optical (outer region) and x-ray (inner region) IDV in AGN.

The initial conditions also have strong influences on the behaviour of the intensity of the emitted radiation. The rise time in the flaring phase decreases monotonically with the mass of the perturber. This trend is roughly linear in Keplerian disks, but the dependence of rise time of $q$ ($q \equiv M_{\text{pert}}/M_{\text{BH}}$) is much weaker in constant angular momentum disks. In the later fluctuating phase, larger amplitude and more rapid variability is produced by more massive perturbers in the Keplerian disk, where the relationship between the rapid fluctuation timescale and $q$ seems roughly linear. The opposite trend appears to be true for the constant angular momentum disks. For low $q$, the dissipation of angular momentum through non-axisymmetric instabilities is insignificant and this causes higher frequency but lower amplitude fluctuations. For high $q$, the equivalent viscosity is stronger, which produces larger amplitude but slower, intensity variations.

### 1.4.3 Plasma processes

Under certain circumstances, coherent plasma processes, such as Stimulated Raman Scattering (SRS) or Stimulated Brillouin Scattering (SBS), may play an important part in rapid variability (Krishan and Wiita, 1990). For high brightness temperature, $T_B$ sources such as pulsars and many blazars, the amplitude of the electric field is large enough to create non-linear effects in the plasma. The SRS process involves the scattering of EM or Langmuir waves to produce coherent radiation over a wide range of frequencies. Transitions between this coherent radiation and individual scattering via the Inverse Compton process can be very fast (Gangadhara and Krishan, 1995; Krishan and Wiita 1994). The conditions necessary for SRS to occur are possible in accretion flows onto SMBHs in AGN, but scattering is usually so severe for reasonable densities that it is difficult for this radiation to escape so that it can be detected. (Levinson and Blandford, 1995).

One type of plasma process that could be important for rapid variability involves oscillations in the plasma itself. If accretion disks around SMBHs have coronae similar to those of the Sun, then magnetoacoustic oscillations of coronal loops can produce fluctuations on timescales from hours to years. These loops are subject to both sausage and kink instabilities. The fast
modes of these magnetoacoustic waves can yield non-thermal emission that
could range from the mm to UV bands and would show very weak polarisation.
Such coronal loops could also produce flares with significant variations.
Krishan and Witta concluded that this microinstability driven mechanism is
able to produce powerful flares, but for parameters expected for AGN coro-
nae it would give timescales ranging from weeks to years. Such emission
would be concentrated in the X-ray band and is unlikely to be significant for
optical rapid variability.

Another class of processes depends upon EM waves acting to modulate
themselves. These waves modify the plasma properties and, in turn the
plasma reacts upon the "pump" wave producing a non-linear active medium
and additional EM waves which cause temporal variability in the emerging
radiation.

Another plasma process that can also be relevant to observed fluctuations
in radiation intensity and polarisation is resonance absorption but the chance
of observing this phenomenon is very small. This process occurs when an
EM wave enters a plasma and describes the partial conversion of the photonic
energy into electron plasma waves. When p-polarised light penetrates such
a plasma, part of the wave is absorbed, but the refracted wave undergoes a
change in polarisation. For AGN this polarisation change can be important
and rapid for radio wavelenghts penetrating broad line emission clouds or
reprocessed by accretion disks in the vicinity of a SMBH (Krishan and Wiita
1994).

1.5 Relativistic jet based models

A large majority of RLQs appear to have a core-jet type structure. The
widely accepted interpretation is that the emission arises from the well-
collimated jets of non-thermal plasma flowing out from the nucleus at rela-
tivistic speeds. This process is called relativistic beaming and it occurs when
gas flowing at mildly relativistic speed directs its emission preferentially along
its direction of motion.

Under the standard relativistic jet model, the Doppler beaming factor, \( \delta \),
is given by

\[
\delta = \left[ \gamma (1 - \beta \cos \theta) \right]^{-1}
\]

(1.4)

where \( \gamma = (1 - \beta^2)^{-1/2} \), \( \beta = v/c \), and is the bulk velocity, \( \theta \) is the angle
between the velocity vector and the line of sight. The Doppler factor has a
strong dependence on the viewing angle (as shown in figure 1.2), which gets stronger for larger Lorentz factors. For $0 \deg \leq \theta \geq 90 \deg$, $\delta$ ranges between

$$\delta_{\text{min}} = \delta(90 \deg) = 1/\gamma$$

and

$$\delta_{\text{max}} = \delta(0 \deg) = (1 + \beta)\gamma$$

Given a value of $\delta$, a lower limit to $\gamma$ is given by the condition $\delta \leq \delta_{\text{max}}$; that is,

$$\gamma \geq 1/2(\delta + 1/\delta)$$

It can also be shown that for any value of $\gamma$,

$$\sin \theta \leq 1/\delta$$

which gives the useful upper limit to $\theta$ if $\delta > 0$.

In the radio maps, the core itself is a very compact, stationary component at one end with a series of knots extending more or less in the direction of the jet. It is two or three orders of magnitude larger than the dimension of the central engine according to the accretion disks around SMBHs theory. However, jets cannot be considered in isolation from disks. It is assumed that they are a natural by-product of disk formation. It has also been suggested that they may even provide a means by which the gas in accretion disk loses angular momentum, so that it can continue to accrete. The knots tend to become more diffuse the farther they are from the core. In most sources, knots trace out an essentially linear jet, but some sources also show twisted jets. Typically compact jets either point directly or curve toward the extended component. Figure 1.3 shows an example of a straight compact jet and the jet in figure 1.4 shows pronounced twists (Marscher 1988).

Compact jets are overwhelmingly one-sided. The predicted jet/counter-jet ratio (i.e., the ratio between the approaching and receding jets), can be expressed in terms of $\delta$ and $\beta_a$ as

$$J = (\beta_a^2 + \delta^2)^p$$

where

$$\beta_a = (\beta \sin \theta)/(1 - \beta \cos \theta)$$

The dependence on the viewing angle is very strong since $J \sim \delta^{2p}$. For example, the jet:counterjet brightness ratio is observed to exceed 1600 in the case of 3C 345 (Rantakyro et al., 1992).
Figure 1.2: Plot of Doppler factor, $\delta$ Vs the viewing angle, $\theta$ showing the strong dependence of the Doppler factor on the viewing angle for different values of the Lorentz factor, $\gamma$. 
Figure 1.3: Example of a straight compact jet (VLBI image of the core-jet quasar NRAO 140 at a wavelength of 6 cm at two epochs).
Figure 1.4: VLBI image at 6cm wavelength of the twisted compact jet of the quasar 1156+295.
The opening angle, $\theta_{op}$ of a jet is inversely proportional to $\gamma$ therefore faster jets are better collimated with $\theta_{op}$ being small. Conversely, slower jets tend to be wider with larger values of $\theta_{op}$.

### 1.5.1 Doppler boosting of flux

The Doppler Factor, $\delta$, relates intrinsic and observed flux for a source moving at relativistic speed $v = \beta c$ (section 1.5). For an approaching source, time intervals measured in the observer frame are shorter than in the rest frame (even allowing for time dilation) because the emitter catches up to its own photons:

$$ t = \delta^{-1} t' \quad (1.11) $$

where primed quantities refer to the rest frame of the source. Since the number of wavefronts per unit time is constant, the emission is blue-shifted:

$$ \nu = \delta \nu' \quad (1.12) $$

The intensity enhancement or the Doppler boosting is an even more severe effect because $I_{\nu}/\nu^3$ is a relativistic invariant, and the transformation of specific intensity is:

$$ I_{\nu}(\nu) = \delta^3 I_{\nu}'(\nu') \quad (1.13) $$

and broad band fluxes are obtained from integrating (equation 1.13) over frequency, since $d\nu = \delta d\nu'$ (equation 1.12), these are boosted by another factor of $\delta$:

$$ F = \delta^4 F' \quad (1.14) $$

The variability in AGN is frequently measured by the change in flux over a given period of time, which from equations (1.14) and (1.11) is given by:

$$ \Delta F/\Delta t = \delta^5 (\Delta F'/\Delta t') \quad (1.15) $$

### 1.5.2 Shock-in-Jet models

The long term variability of blazars in the radio band is very well modelled in term of shocks propagating down jets (Marscher and Gear, 1985). This approach can explain the big outbursts that occur on yearly timescales in terms of disturbances in relativistic flows. The synchrotron emission from the plasma moving towards us at a velocity $\beta c$ and the Lorent Factor $\gamma$ is
strongly exaggerated, with the flux being proportional to $\delta^4$ (equation 1.14 section). In the radio VLBI maps, sources can be resolved into a series of outward moving knots that are interpreted as shock locations within the jet. The frequently observed apparent superluminal motion can be explained if the flow and shock velocities are relativistic and $\theta$ is small (Hughes, Aller and Aller, 1991).

The brightness temperatures estimated from these longer scale fluctuations can be reconciled with the inverse Compton limit of $T_B < 10^{12}$ K if $\gamma$ is in the range 3-10, which is adequate to explain the superluminal motions. These relativistic jets solve other problems, such as the observed relative paucity of X-rays vs Synchrotron Self Compton (SSC) predictions and the single-sidedness of radio jets in powerful sources. However, the microvariability observed in some RLQs infer $T_B \approx 10^{21}$ K (Rantakyro et al. 1994). Within the standard shock-in-jet model, even $T_B = 10^{19}$ K would require $\gamma > 100$, which is hard to account for and is never indicated by the apparent velocity measurements. In jets the brightness temperature is related to a transverse scale (for small $\theta$), so the pre-existing structures could be illuminated by the moving shock simultaneously, then the simple causality constraint may not apply, and if the scale is roughly the size of the jet radius in the source's rest frame, $\gamma \approx 10$ may still work (Qian et al., 1991). But this requires very special focussing and geometrical alignments, so this is very unlikely (Marscher 1992). Also, even bulk $\gamma > 100$ may be allowed in hydromagnetic acceleration scenarios for jets (Begleman 1991). However such jets can preserve synchrotron emission and IDV only if they have extremely high kinetic energy fluxes and very low radiative efficiencies, so this does not explain observed microvariability very convincingly either.

On the other hand these models not only have done an excellent job of fitting the total flux at several frequencies for quite a few radio sources, but also can explain many of the changes in the polarised flux and polarisation position angle for longer scale variabilities observed in RLQs (Hughes, Aller and Aller, 1991). Figure 1.4 shows the basic geometry of the relativistic jet model.

### 1.5.3 Turbulent jets

It has been suggested that IDV may be caused by smaller, more frequent, disturbances propagating down the jet. An extension of this idea has been proposed by Marscher, Gear, and Travis (Marscher and Gear, 1985). They
Figure 1.5: Basic geometry of the relativistic jet model as viewed from a direction transverse to the axis (Marscher 1992).
suggest that because the Reynolds number in a relativistic jet should be very high, the jet plasma ought to be very turbulent. The shock will therefore come across regions of different densities, magnetic field strengths, and velocities, and this could produce variations in the observed flux. The effect that this has on the time variability depends on the amplitude and power spectrum of the turbulence as well as on the thickness of the shocked emission region. As the disturbance propagates down the jet, it brightens at sites where it encounters density and/or magnetic field enhancements and fades where it encounters diminishments. It is mainly the magnetic field fluctuations that amplify or reduce the flux density at a given location in the shock (Marscher, Gear and Travis, 1992). Numerical experiments carried out by Marscher et al., also show that this could yield fluctuations with timescales as short as \( \approx \frac{x}{(\gamma c)} \), with \( x \) the size of a turbulent eddy within the jet, as long as the shock is very thin.

The timescales of this proposed type of fluctuation are shorter and their amplitudes larger at higher frequencies because they arise from smaller values of \( x \) in this scheme. This may explain IDV seen in the optical but it is unlikely that shocks can be thin enough to cause fluctuations with day-like timescales in the cm wavelengths.

### 1.6 Why search for ROV in RQQs?

As already noted quasars can be divided into two types: RLQs and RQQs based on their radio emission. The \( R \) parameter which is the ratio of the total radio luminosity at 5GHz to the B-band optical flux is typically, \( R \leq 1 \) for RQQs and \( R \approx 100 \) RLQs (Kellerman et al., 1989, 1994). The separation between the RLQs and RQQs is not absolute, and objects of intermediate \( R \) values, known as RIQs, certainly exist (Hooper et al., 1995; Falcke et al., 1996).

Radio mapping of many RLQs reveals a double, often collinear morphology on arcsec scales (Bridle et al. 1994) comprising of a bright, compact, partially opaque flat-spectrum core component and an extended component which is optically thin and steep spectrum. Often a jet bridges the compact and extended radio components. In contrast radio images of RQQs often merely show a weak component coincident with the optical quasar nucleus.

The question arises what can be said about the nature of the emission mechanisms of RLQs as compared to RQQs considering that the total radio
luminosity in RQQs is usually two or three orders of magnitude less than that detected for RLQs, with similar ratios at many other wavelengths. Are RQQs and RLQs two different types of cosmic creatures powered by different processes or is the first a powered down version of the latter?

The idea of an accretion-fuelled SMBH as the central engine for RLQs is well accepted since the observation of superluminal motion and other indicators of high bulk lorentz factors have established the existence of relativistic jets. For RQQs the debate is still pretty much open. It has been suggested by Terlevich et al. that RQQs can be powered by circumnuclear starbursts. But for this to be feasible it would require a very high density of SNRs at peak luminosity.

Kellerman et al. (1994) imaged BQS sources using the VLA and detected that some of the RQQs in the sample have compact core type components seen in RLQs. Falcke et al. (1996) suggest that RIQs may the boosted counterparts of RQQs, Barvainis et al. (1996) find that 40% of RQQs in their sample have either flat or inverted radio spectra, Falcke et al. (1997) also report the existence of a jet in Mrk 34 (which is Seyfert 2 galaxy but with OIII luminosity typical for RQQs) after a long integration VLA map at 3.5 cm, Blundell and Beasley 1996, 1998 find evidence supportive of central engines in RQQs resembling those found in RLQs. So, there is growing evidence that the nature of the RQQ powerhouse may be similar to central engine hypothesised for RLQs. The piece missing from the puzzle is a direct observation of a jet implying superlumial motion and relativistic beaming. Indeed, if RQQs do possess such structures then statistically, some of them should be facing towards us and such observations should be possible. But there are observational difficulties for these weak sources. Even the VLBI observations of RQQs lack the sensitivity to detect additional components besides the core (Falcke et al. 1997).

Many RLQs, especially blazars, show ROV at timescales as short as hours. These variability observations have been important in supporting, in the development of, and in the constraining of the relativistic jet based models proposed for RLQs. Therefore similar type of optical variability if observed in RQQs would provide essential support for the hypothesis that RQQs and RLQs have similar central engines and RQQs also harbour jets, but these jets are weaker than those found in RLQs. The confirmation of the existence of jets in RQQs may lead to a unified scheme that encompasses all AGN.

So, we have undertaken a programme to address this issue by searching for ROV in 16 core-dominated flat-spectrum RQQs in V, R and B bands
using wide-field CCDs which provide several suitable stars as comparisons for differential photometry. It should be pointed out that some authors like Gopal-Krishna, Wiita and De Diego have looked for microvariability in RQQs with the premise that they lack jets and hence any observed fluctuations, they suggest would be supportive of the models predicting variability arising from disk-based instabilities rather than jets. Obviously, a large structure like the accretion disk would contribute significantly to the overall RQQ emission. In a variability study alone one would not necessarily be able to discriminate between whether the variability observed arises from a jet-type component or from the instabilities on the accretion disk, one can merely make the observations and then see which model best describes the observations. But if the central engines of RQQs are similar to those of RLQs then core-dominated flat-spectrum RQQs should show variability with similarities to those seen in core-dominated flat-spectrum RLQs, and coupled with other evidence such as higher sensitivity radio imaging, this type of variability if observed would present strong evidence in the favour of RQQs harbouring jets.
Chapter 2

Data acquisition and reduction

2.1 Observations

The observations described in this work were carried out over 3 years, using the 1.0 m Jacobus Kapteyn Telescope (JKT) which is part of the Isaac Newton Group of telescopes on the Island of La Palma in the Canaries, and the 2.2 m telescope in the German-Spanish Observatory based in Calar Alto in mainland Spain. The sample consists of 16 radio quiet quasars. The 1996 and 1997 observations at the JKT were made using the EEV7 CCD at the cassegrain focus with $1240 \times 1152$ pixels yielding an image scale of $0.30''$ per pixel and a field of view of $6' \times 5.8'$. The data from the 2.2m German-Spanish telescope was obtained using TEK6 CCD with $1024 \times 1024$ pixels and an image scale of $0.66''$, yielding a field of view of $12' \times 12'$. The TEK4 CCD with $1024 \times 1024$ pixels was used for the observations taken at the JKT in 1998/1999. This had a field of view of $6' \times 6'$ with an image scale of $0.33''$ per pixel. The observational details are summarised in tables 2.1-2.7.
Table 2.1: Summary of the Observations made at the 2.2m in Calar Alto, from 08/06/96 to 14/06/96.

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<td>V</td>
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Table 2.2: Summary of the Observations made at the 1.0m JKT in La Palma, from 27/05/96 to 03/06/96.

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Table 2.3: Summary of the Observations made at the 1.0m JKT in La Palma, from 09/04/97 to 16/04/97.

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Table 2.4: Summary of the Observations made at the 1.0m JKT in La Palma, from 02/01/98 to 07/01/98.

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<td>30-500</td>
</tr>
<tr>
<td>PG1247+268</td>
<td>12 47 39.3</td>
<td>26 47 28</td>
<td>V</td>
<td>53</td>
<td>30-300</td>
</tr>
<tr>
<td>PG1334+246</td>
<td>13 34 57.4</td>
<td>24 38 19</td>
<td>V</td>
<td>3</td>
<td>400</td>
</tr>
<tr>
<td>PG1426+015</td>
<td>14 26 33.8</td>
<td>01 30 27</td>
<td>V</td>
<td>6</td>
<td>10-100</td>
</tr>
</tbody>
</table>
Table 2.5: Summary of Observations made at the 1.0m JKT in La Palma, from 06/05/98 to 13/05/98.

<table>
<thead>
<tr>
<th>Name</th>
<th>RA (1950)</th>
<th>Dec (1950)</th>
<th>Band</th>
<th>Number of Observations</th>
<th>Exp. Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG1634+706</td>
<td>16 34 51.5</td>
<td>70 37 37</td>
<td>B</td>
<td>63</td>
<td>120-250</td>
</tr>
<tr>
<td>PG1634+706</td>
<td>16 34 51.5</td>
<td>70 37 37</td>
<td>R</td>
<td>67</td>
<td>50-150</td>
</tr>
<tr>
<td>E1821+643</td>
<td>18 21 41.8</td>
<td>64 19 10</td>
<td>B</td>
<td>196</td>
<td>70-150</td>
</tr>
<tr>
<td>E1821+643</td>
<td>18 21 41.8</td>
<td>64 19 10</td>
<td>R</td>
<td>188</td>
<td>50-150</td>
</tr>
</tbody>
</table>

Table 2.6: Summary of the Observations made at the 1.0m JKT in La Palma, from 26/05/99 to 29/05/99.

<table>
<thead>
<tr>
<th>Name</th>
<th>RA (1950)</th>
<th>Dec (1950)</th>
<th>Band</th>
<th>Number of Observations</th>
<th>Exp. Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG0903+129</td>
<td>09 03 19.95</td>
<td>12 57 06</td>
<td>V</td>
<td>6</td>
<td>60-200</td>
</tr>
<tr>
<td>PG1148+549</td>
<td>11 48 42.6</td>
<td>54 54 13</td>
<td>V</td>
<td>4</td>
<td>60-400</td>
</tr>
<tr>
<td>PG1247+268</td>
<td>12 47 39.0</td>
<td>26 47 28</td>
<td>V</td>
<td>8</td>
<td>350-400</td>
</tr>
<tr>
<td>PG1407+265</td>
<td>14 07 07.7</td>
<td>26 32 30</td>
<td>V</td>
<td>4</td>
<td>60-300</td>
</tr>
<tr>
<td>PG1426+015</td>
<td>14 26 33.8</td>
<td>01 30 27</td>
<td>V</td>
<td>4</td>
<td>60-250</td>
</tr>
<tr>
<td>PG1634+706</td>
<td>16 34 51.5</td>
<td>70 37 37</td>
<td>B</td>
<td>3</td>
<td>350</td>
</tr>
<tr>
<td>PG1634+706</td>
<td>16 34 51.5</td>
<td>70 37 37</td>
<td>R</td>
<td>3</td>
<td>300</td>
</tr>
<tr>
<td>PG1634+706</td>
<td>16 34 51.5</td>
<td>70 37 37</td>
<td>V</td>
<td>4</td>
<td>60-100</td>
</tr>
<tr>
<td>E1821+643</td>
<td>18 21 41.8</td>
<td>64 19 10</td>
<td>B</td>
<td>5</td>
<td>100-200</td>
</tr>
<tr>
<td>E1821+643</td>
<td>18 21 41.8</td>
<td>64 19 10</td>
<td>R</td>
<td>3</td>
<td>180-200</td>
</tr>
<tr>
<td>E1821+643</td>
<td>18 21 41.8</td>
<td>64 19 10</td>
<td>V</td>
<td>11</td>
<td>60</td>
</tr>
</tbody>
</table>
Table 2.7: Summary of the total number of Observations acquired for each RQQ in our sample.

<table>
<thead>
<tr>
<th>Name</th>
<th>Band</th>
<th>Total number of Observations</th>
<th>Number of observing epochs</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG0003+199</td>
<td>V</td>
<td>53</td>
<td>1</td>
</tr>
<tr>
<td>PG0157+001</td>
<td>V</td>
<td>23</td>
<td>1</td>
</tr>
<tr>
<td>PG0804+761</td>
<td>V</td>
<td>99</td>
<td>2</td>
</tr>
<tr>
<td>PG0903+129</td>
<td>V</td>
<td>48</td>
<td>2</td>
</tr>
<tr>
<td>PG1116+215</td>
<td>V</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>PG1148-006</td>
<td>V</td>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td>PG1148+549</td>
<td>V</td>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>PG1222+229</td>
<td>V</td>
<td>28</td>
<td>1</td>
</tr>
<tr>
<td>PG1247+268</td>
<td>V</td>
<td>68</td>
<td>2</td>
</tr>
<tr>
<td>PG1334+246</td>
<td>V</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>PG1407+265</td>
<td>V</td>
<td>56</td>
<td>4</td>
</tr>
<tr>
<td>PG1416-129</td>
<td>V</td>
<td>26</td>
<td>2</td>
</tr>
<tr>
<td>PG1426+015</td>
<td>V</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>PG1634+706</td>
<td>V</td>
<td>68</td>
<td>4</td>
</tr>
<tr>
<td>E1821+643</td>
<td>V</td>
<td>137</td>
<td>4</td>
</tr>
<tr>
<td>PG2112+069</td>
<td>V</td>
<td>18</td>
<td>2</td>
</tr>
<tr>
<td>PG1634+706</td>
<td>B</td>
<td>63</td>
<td>2</td>
</tr>
<tr>
<td>E1821+643</td>
<td>B</td>
<td>196</td>
<td>2</td>
</tr>
<tr>
<td>PG1634+706</td>
<td>R</td>
<td>67</td>
<td>2</td>
</tr>
<tr>
<td>E1821+643</td>
<td>R</td>
<td>191</td>
<td>2</td>
</tr>
</tbody>
</table>
2.2 Selection of sources

In recent years there have been a handful of research efforts to search for short-term/small amplitude optical variability in RQQs (mainly by authors Wiita, Gopal-Krishna, Ram Sagar, and Jang-Miller, Rabbette et al. (section 1.3). However these studies have been conducted to search for evidence that supports models that propose that optical variability in RQQs arises from disk-based instabilities such as hot spots etc (with the exception of Rabbette et al., 1998). Since it is currently accepted that RQQs do not have jets, they have been the obvious choice to look for accretion disk induced variability and therefore the choice of objects for these investigations has been of those that are "definite" RQQs with steep radio spectra. Our approach has been somewhat different to these previous studies. The starting premise for our investigation is that RQQs may harbour weak jets. With this in mind we've selected objects, primarily, if they have either flat/inverted radio spectra (Barvainis et al. 1996) or/and show evidence of a compact core with possibly one-sided extended radio features emanating from the core (Kellermann 1994). It is currently accepted that flat radio spectra/compact cores are related to the presence of a jet. Typically these features are more common to RLQs. Our object sample was created from the lists of Kellermann et. al (1994) and Barvainis et. al (1996) with the selected objects also satisfying the following criteria:

(i) \( m_B \leq 16.0 \) to allow for good signal-to noise ratio, \( S/N \) to be attained in exposure times 1 – 10 mins with the telescopes used, so that these objects can be studied for possible rapid variations within a night; (ii) radio to optical ratio, \( R \leq 10 \) so that they meet the RQQ classification criteria; (iii) \( M_B \leq -22.0 \) so that we are dealing with luminous RQQs and not Seyfert galaxies (Kellermann et al., 1989) with the exception of PG0003+199 and PG0923+129 which lie at the edge of this classification criteria and have been categorised as Seyferts by some authors, however they display signs of a compact core (Kellermann 1994) and have flat or inverted radio spectra (Barvainis et al., 1996) and hence we have considered them suitable candidates for this campaign; (iv) at least four or preferably more adequately bright stars could be located within the CCD frame encompassing the RQQ so that a reasonable number of reference stars for differential photometry was available.

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Table 2.8: Table displaying a summary of RQQ properties. Column 2: Apparent B-band magnitude, column 3: Absolute B-band magnitude, column 4: Redshift, column 5: The radio luminosity at 5 GHz, column 6: The R parameter. The superscripts are added where there are conflicting values for the given parameter. Superscript 'a' refers to the values obtained from Kellerman et al., 1994 and 'b' refers to Barvainis et al., 1996.

<table>
<thead>
<tr>
<th>Name</th>
<th>$m_B$</th>
<th>$M_B$</th>
<th>$z$</th>
<th>$L_{radio}$ $(WHz^{-1})$</th>
<th>$L_{radio}/L_{optical}$</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG0003+199</td>
<td>13.75</td>
<td>-22.13</td>
<td>0.025</td>
<td>$1.1 \times 10^{22}$</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>PG0157+001</td>
<td>15.69$^a$, 16.15$^b$</td>
<td>-24.76$^a$, -23.80$^b$</td>
<td>0.164</td>
<td>$9.2 \times 10^{23}$</td>
<td>2.1$^a$, 5.1$^b$</td>
<td></td>
</tr>
<tr>
<td>PG0804+761</td>
<td>15.15</td>
<td>-23.74</td>
<td>0.1</td>
<td>$1.0 \times 10^{23}$</td>
<td>0.6$^a$, 0.3$^b$</td>
<td>2.1</td>
</tr>
<tr>
<td>PG0903+129</td>
<td>14.93</td>
<td>-21.27</td>
<td>0.029</td>
<td>$3.6 \times 10^{23}$</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>PG1116+215</td>
<td>15.17</td>
<td>-24.96</td>
<td>0.177</td>
<td>$3.8 \times 10^{23}$</td>
<td>0.72$^a$, 0.5$^b$</td>
<td></td>
</tr>
<tr>
<td>PG1148-006</td>
<td>17.77</td>
<td>-25.61</td>
<td>0.8</td>
<td>$2.9 \times 10^{23}$</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>PG1148+549</td>
<td>15.82</td>
<td>-27.97</td>
<td>0.969</td>
<td>$4.9 \times 10^{24}$</td>
<td>0.59</td>
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</tr>
<tr>
<td>PG1222+229</td>
<td>15.49</td>
<td>-29.87</td>
<td>2.046</td>
<td>$2.0 \times 10^{26}$</td>
<td>4.1$^a$, 2.6$^b$</td>
<td>0.36</td>
</tr>
<tr>
<td>PG1247+268</td>
<td>15.53</td>
<td>-29.82</td>
<td>2.038</td>
<td>$1.7 \times 10^{25}$</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>PG1334+246</td>
<td>15.01</td>
<td>-23.1</td>
<td>1.08</td>
<td>$8.0 \times 10^{24}$</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>PG1407+265</td>
<td>15.73</td>
<td>-28.06</td>
<td>0.94</td>
<td>$3.1 \times 10^{25}$</td>
<td>3.4$^a$, 2.5$^b$</td>
<td></td>
</tr>
<tr>
<td>PG1416-129</td>
<td>15.4</td>
<td>-24.04</td>
<td>0.129</td>
<td>$2.6 \times 10^{25}$</td>
<td>1.1$^a$, 0.3$^b$</td>
<td></td>
</tr>
<tr>
<td>PG1426+015</td>
<td>15.67</td>
<td>-23.51</td>
<td>0.086</td>
<td>$3.8 \times 10^{22}$</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>PG1634+706</td>
<td>14.9</td>
<td>-29.57</td>
<td>1.334</td>
<td>$1.6 \times 10^{25}$</td>
<td>0.44$^a$, 0.2$^b$</td>
<td></td>
</tr>
<tr>
<td>E1821+643</td>
<td>14.4</td>
<td>-27.0</td>
<td>0.297</td>
<td>$4.8 \times 10^{23}$</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>PG2112+059</td>
<td>15.84</td>
<td>-26.26$^a$, -26.70$^b$</td>
<td>0.466</td>
<td>$8.2 \times 10^{23}$</td>
<td>0.32</td>
<td></td>
</tr>
</tbody>
</table>

2.3 Notes on individual objects from previous studies

2.3.1 PG0003+199

PG 0003+199 is classed as a type 1 Seyfert in the literature. Kellerman et al., 1994 report that the radio source is compact and unresolved and Miller et al., 1993 report that it has a flat radio spectrum.
2.3.2 PG0157+001

This RQQ is unresolved and appears as a double source in VLA radio images (Kukula et al., 1998; Kellerman et al., 1994) and is reported as having a curved upwards radio spectra (Barvainis et al., 1996).

2.3.3 PG0804+761

VLA (Kellerman et al., 1994) images show this to be a compact object with an elongated source with a peak flux density of 11 mJy located (100 Kpc projected separation) away which may be part of the source. Kukula et al., 1998 give values of $\alpha$ of 0.2, 0.8, and 0.4 for $\alpha_{4.8}^{14}$, $\alpha_{8.4}^{4.8}$ and $\alpha_{8.4}^{14}$ GHz respectively. Giveon et al., 1999 report that PG0804+761 is variable ($\approx 0.3$ mag) at yearly timescales in both B and R bands.

2.3.4 PG0923+129

This object is also classified as a type 1 Seyfert. VLA images show two components in an asymmetric structure with a component separation of between 40 to 25 Kpc (Kellerman et al., 1994). Giveon et al., 1999 report that this object is variable ($\approx 0.5$ mag) at yearly timescales in both B and R bands.

2.3.5 PG1116+215

This RQQ appears resolved in the VLA images and shows a large linear structure $\approx 100$ kpc in extent (Kellerman et al., 1994) and the host of this RQQ is an elliptical galaxy (McLeod and Rieke 1995). Kukula et al., 1998 give values of $\alpha$ of 0.8, 0.7, and 0.8 for $\alpha_{4.8}^{14}$, $\alpha_{8.4}^{4.8}$ and $\alpha_{8.4}^{14}$ GHz respectively.

2.3.6 PG1148-006

The RQQ has inverted radio spectra and is found to be variable at radio wavelengths at yearly timescales (Barvainis et al., 1996).

2.3.7 PG1148+549

Kellerman et al., 1994 report that this RQQ is coincident with a resolved radio component and has a complex radio spectrum (Barvainis et al., 1996).
2.3.8 PG1222+229

This is the most luminous RQQ in our sample (table 2.8). Blundell et al., 1998 report structures indicative of jets from their VLBI imaging campaign and find a brightness temperature of \(8.3 \times 10^7\) K. Barvainis et al., 1996 find that it has a complex radio spectrum and is variable on yearly timescales in the radio.

2.3.9 PG1247+268

Barvainis et al., 1996 find that the RQQ has flat radio spectrum.

2.3.10 PG1334+246

VLA observations for this RQQ reveal an unresolved source with a maximum flux density of 7 mJy at 5GHz. PG1334+246 has been observed on several occasions by ROSAT and was found to vary by a factor of 4.1 in approximately one year (Brandt et al., 1996). ASCA observations revealed this RQQ also shows blazar type rapid variations in x-ray wavelengths (Brinkman et al., 1996).

2.3.11 PG1407+265

Blundell et al., 1998 find structures indicative of jets from their VLBI imaging campaign and find a brightness temperature of \(1.1 \times 10^9\) K. The optical quasar is coincident with an unresolved compact component and a 1.6 mJy component lying about 57 arcsec away is not believed to be related to the RQQ (Kellerman et al., 1994). The radio spectrum is consistent with a flat or inverted spectrum (Barvainis et al., 1996).

2.3.12 PG1416-129

This is a Broad Absorption Line Quasar (BALQ) (Turnshek and Grillmair 1986). OSSE observations (Staubert and Maisack 1996) showed that the RQQ was variable on timescale of days at energies above 50 Kev. VLA observations show that the radio source consists of an unresolved core coincident with an extended component which is assumed to be unrelated to the RQQ (Kellerman et al., 1994) and it was found to have varied by a factor
of 4.5 over ten years and Barvainis et al., 1996 also found the source to be variable on yearly timescales. The radio spectrum is consistent with a flat or inverted spectrum (Barvainis et al., 1996).

2.3.13 PG1426+015

Giveon et al. 1999 find that the RQQ is variable in B and R on timescale of years. Barvainis et al., 1996 find that it has a slightly curved but more or less a flat radio spectrum.

2.3.14 PG1634+706

The radio source appears resolved and appears to show a large linear structure (≈ 300 kpc) (Kellerman et al., 1994). Barvainis et al., 1996; 1989 report that PG 1634+706 has flat radio spectrum from both their studies.

2.3.15 E1821+643

E 1821+643 lies at the centre of a giant elliptical galaxy and resides in a environment of rich clusters (Hutchings and Neff 1991). Lacy et al., 1992; Blundell et al., 1996 show that the RQQ is coincident with a compact (on milliarcsecond scale from VLBA measurements) source with a possible one-sided jet. Blundell et al., 1996 give of $1.4 \times 10^9$ K as the lower limit for the brightness temperature. Papadopoulos et al., 1994 found clear evidence for extended radio emission and found a one-sided structure, possibly a jet emanating from the core.

2.3.16 PG2112+059

Rabbette et al., 1998 observed that PG 2112+059 varied by 0.18 mag in V-band between September 1992 and June 1996.

The general properties of the RQQs in our sample are summed up in Table 2.8.

2.4 Selection of comparisons and finding charts

When selecting appropriate reference stars during the data reduction procedure, we considered the following: (i) none of the reference stars in any of the
frames are saturated; (ii) the counts in reference stars for any given frame had
to remain well below the non-linear limit of the CCD. For the TEK6 at Calar
Alto, the response of the CCD was linear up to $40K$, for both the EEV7 and
TEK4 CCDs used at the JKT the response becomes non-linear at $60K$; (iii)
there was at least one reference star with similar apparent brightness as the
RQQ; (iv) that a given reference star was sufficiently far away from other
objects in the field, so that aperture photometry could be performed; (v)
that the selected stars did not lie close to the edge of the CCD in any given
frame. (vi) that none of the selected stars were intrinsically variable, but this
usually only becomes apparent after data reduction (see section 2.4.2).

2.5 Finding charts

Finding charts displaying the locations of the RQQs and reference stars on
the CCD frames for all the datasets are shown in figures 2.1 to 2.42).

Figure 2.1: CCD image showing the positions of PG0003+199 (labelled
RQQ) and the reference stars ($R_i$) for V-band, La Palma, January 1998.
Figure 2.2: CCD image showing the positions of PG0157+001 and the reference stars for V-band, La Palma, January 1998.

Figure 2.3: CCD image showing the positions of PG0804+761 and the reference stars for V-band, La Palma, April 1997.
Figure 2.4: CCD image showing the positions of PG0804+761 and the reference stars for V-band, La Palma, January 1998.

Figure 2.5: CCD image showing the positions of PG0923+129 and the reference stars for V-band, La Palma, January 1998.
Figure 2.6: CCD image showing the positions of PG0923+129 and the reference stars for V-band, La Palma, May 1999.

Figure 2.7: CCD image showing the positions of PG1116+215 and the reference stars for V-band, Calar Alto, June 1996.
Figure 2.8: CCD image showing the positions of PG1116+215 and the reference stars for V-band, La Palma, May/June 1996.

Figure 2.9: CCD image showing the positions of PG1148-006 and the reference stars for V-band, La Palma, April 1997.
Figure 2.10: CCD image showing the positions of PG1148+549 and the reference stars for V-band, La Palma, January 1998.

Figure 2.11: CCD image showing the positions of PG1148+549 and the reference stars for V-band, La Palma, May 1999.
Figure 2.12: CCD image showing the positions of PG1222+229 and the reference stars for V-band, La Palma, April 1997.

Figure 2.13: CCD image showing the positions of PG1247+268 and the reference stars for V-band, La Palma, January 1998.
Figure 2.14: CCD image showing the positions of PG1247+268 and the reference stars for V-band, La Palma, May 1999.

Figure 2.15: CCD image showing the positions of PG1334+246 and the reference stars for V-band, La Palma, April 1997.
Figure 2.16: CCD image showing the positions of PG1334+246 and the reference stars for V-band, La Palma, January 1998.

Figure 2.17: CCD image showing the positions of PG1407+265 and the reference stars for V-band, Calar Alto, June 1996.
Figure 2.18: CCD image showing the positions of PG1407+265 and the reference stars for V-band, La Palma, May/June 1996.

Figure 2.19: CCD image showing the positions of PG1407+265 and the reference stars for V-band, La Palma, April 1997.
Figure 2.20: CCD image showing the positions of PG1407+265 and the reference stars for V-band, La Palma, May 1999.

Figure 2.21: CCD image showing the positions of PG1416-129 and the reference stars for V-band, Calar Alto, June 1996.
Figure 2.22: CCD image showing the positions of PG1416-129 and the reference stars for V-band, La Palma, April 1997.

Figure 2.23: CCD image showing the positions of PG1426+015 and the reference stars for V-band, La Palma, January 1998.
Figure 2.24: CCD image showing the positions of PG1426+015 and the reference stars for V-band, La Palma, May 1999.

Figure 2.25: CCD image showing the positions of PG1634+706 and the reference stars for V-band, Calar Alto, June 1996.
Figure 2.26: CCD image showing the positions of PG1634+706 and the reference stars for $V$-band, La Palma, May/June 1996.

Figure 2.27: CCD image showing the positions of PG1634+706 and the reference stars for $V$-band, La Palma, April 1997.
Figure 2.28: CCD image showing the positions of PG1634+706 and the reference stars for V-band, La Palma, May 1999.

Figure 2.29: CCD image showing the positions of PG1634+706 and the reference stars for B-band, La Palma, May 1998.
Figure 2.30: CCD image showing the positions of PG1634+706 and the reference stars for B-band, La Palma, May 1999.

Figure 2.31: CCD image showing the positions of PG1634+706 and the reference stars for R-band, La Palma, May 1998.
Figure 2.32: CCD image showing the positions of PG1634+706 and the reference stars for R-band, La Palma, May 1999.

Figure 2.33: CCD image showing the positions of E1821+643 and the reference stars for V-band, Calar Alto, June 1996.
Figure 2.34: CCD image showing the positions of E1821+643 and the reference stars for V-band, La Palma, May/June 1996.

Figure 2.35: CCD image showing the positions of E1821+643 and the reference stars for V-band, La Palma, April 1997.
Figure 2.36: CCD image showing the positions of E1821+643 and the reference stars for V-band, La Palma, May 1999.

Figure 2.37: CCD image showing the positions of E1821+643 and the reference stars for B-band, La Palma, May 1998.
Figure 2.38: CCD image showing the positions of E1821+643 and the reference stars for B-band, La Palma, May 1999.

Figure 2.39: CCD image showing the positions of E1821+643 and the reference stars for R-band, La Palma, May/June 1998.
Figure 2.40: CCD image showing the positions of E1821+643 and the reference stars for R-band, La Palma, May 1999.

Figure 2.41: CCD image showing the positions of PG2112+059 and the reference stars for V-band, Calar Alto, June 1996.
2.6 Photometry

All the data is reduced using a set of software routines called PHOTMATE produced within the Astrophysics group in the CIT (see O'Driscoll et al., in prep). PHOTMATE is a user supportive optical photometry data reduction system. It relieves the user of management tasks and provides aids which assist them in their analysis. It is designed to support the user's expertise in examining images and ability to make decisions, such as selection of appropriate reference stars and overall usability of frames. Tasks such as file naming, producing analysis records and compiling results are performed by PHOTMATE. PHOTMATE is written using IRAF's (Image Reduction and Analysis Facility) scripting language CL, consisting of forty scripts. The processing scripts control the operation of existing IRAF processing routines such as ccdred, phot, or mkapfile. See McCarthy 1995 for the details of these routines as applied to our data reduction procedure. At the heart is the IRAF routine phot which is used to perform all the aperture photometry (see section 2.4.1).

Before reducing the data all the frames are carefully examined: (i) for any gradients across the chip using vector plots; (ii) for the availability of suitable reference stars; (iii) for the presence of any spurious structures in
images resulting from unwanted light, although this consideration is almost always taken care of at the observing stage; (iv) to check that the counts in the sources are reasonably above the sky background and below the saturation and non-linearity limit of the CCD.

Before processing, the images are corrected using flat-fields taken either at dusk and/or dawn. This removes any pixel to pixel variations on the ccd chip. A master flat-field frame is produced by averaging as many sky frames as possible with counts lying between $20K - 40K$. A master zero-bias frame is produced by combining several 0sec exposures and is subtracted from all the images to remove the additive d.c. level on the CCD chip.

2.6.1 Aperture photometry

The basic principle of aperture photometry is to first integrate the observed flux from the centre of an object out to a suitable radius, and then to subtract the total contribution of the sky background integrated over the same area from the total integrated flux. This leaves only the flux from the object to calculate an instrumental magnitude. For a statisticallly well behaved CCD image the instrumental magnitude, $mag$ and its error $merr$ are obtained from the following:

$$flux = sum - area \times msky$$

$$mag = zmag - 2.5 \log flux + 2.5 \log itime$$

$$error = ((flux/epadu) + (area \times stdev^2) + (area^2 \times stdev^2/nsky))^{1/2}$$

$$merr = 1.0857 \times (error/flux)$$

where $flux$ = the total number of counts excluding the sky in the aperture,
$sum$ = the total number of counts including the sky in the aperture,
$area$ = the area of the aperture in square pixels,
$msky$ = the sky value per pixel,
$zmag$ = the zero point of magnitude scale and is set to 26,
$itime$ = the exposure time,
$epadu$ = the gain in electrons per analogue to digital units,
$stdev$ = the standard deviation in the sky value per pixel, and
$nsky$ = the number of sky pixels contained within the aperture.

The first term in the equation 1.3 represents the Poisson noise in the object. For bright objects this term dominates the overall measurement of $merr$. The second term represents the error in the background and includes
both the effects of Poisson noise in the sky and the readout noise in the
detector via the measured quantity \( stdev \). The third term represents the effect
of an error in the mean sky. The second term dominates for faint objects,
and the third term can become important if the sky is poorly determined.

To calculate an instrumental magnitude using aperture photometry tech­
nique the following factors are immediately important: (i) no other objects
should be contained inside the aperture; (ii) the sky background flux should
be determined accurately; (iii) the specified aperture should be sufficiently
large so that the seeing, tracking and focus errors do not affect the fraction
of the object's flux that falls outside the aperture.

Choice of aperture

Photometry on the RQQ and reference stars is carried out using concentric
circular apertures of 2.0 – 20.0 pixel radii in steps of 2.0 pixel radius. In some
cases it was necessary to extend the aperture limit to 24 pixel radius. Figure
2.43 shows the magnitudes calculated using PHOT at apertures from 2 to 22
pixel radii for a RQQ and the selected reference stars in a given CCD frame. 
From figure 2.43, we can see that the calculated magnitudes start to level of
at around 12 pixel radii and then remain unchanged as the aperture increases.
Figure 2.44 shows that \( merr \) continues to increase with increasing aperture,
as expected when using the aperture photometry technique. Through this
type of analysis of our data, it was determined that the best \( S/N \) and the
most reliable measurements are obtained using an aperture of 14 pixel radii
corresponding to \( \approx 4.5'' \). In a very few cases larger apertures have been
used due to either very poor seeing conditions or trailing of objects resulting
from poor guiding. Our approach is to compare the lightcurves using several
apertures. This provides us with an additional robustness test for the final
lightcurve.

2.6.2 Differential photometry

Differential photometry consists of comparing an object of interest to the
other objects present on the frames. Given that all the objects are approx­
imately at the same airmass, the first order extinction between two stars
which depends on the difference in airmass is cancelled in differential analysis
(Young et. al, 1974). It is also assumed that any variations due to instru­
mentation will also affect all the sources in a similar manner given that the
Figure 2.43: Displays how the magnitudes calculated by the IRAF phot routine vary with increasing aperture sizes from 2.0 to 22.0 pixel radii, for all of the selected sources for a given dataset.
Figure 2.44: Displays how the errors associated with the calculated magnitudes by the IRAF phot routine vary with aperture sizes from 2.0 to 22.0 pixel radii for all of the selected sources for a given dataset.
response of the CCD detector is approximately homogeneous over the entire chip. Some of the pixel to pixel variations can be normalised using flat-field corrections as mentioned above if the sources are situated on slightly different locations on the chip because of poor guiding or tracking, for instance. One of the main advantages of differential photometry is the relaxation of the stringency on atmospheric conditions, compared with standard stars' photometry. Useful data can be gathered through quite hazy or variable sky conditions. Indeed, this is what we have also found experimentally. On nights of variable conditions where the raw magnitudes for sources seem to fluctuate by as much as $\approx 2 - 3$ mag that differentially data appears well behaved within the error bars.

Traditionally, the approach has been to pick just one comparison star, $R$ and a check star, $C$ as well as the object of interest, $V$. This leads to the production of a differential lightcurve (DLC) by subtracting $V$ observed magnitudes, $m_i$, from $R$ observed magnitudes at corresponding times, $t_i$, e.g. $V_{m,t_i} - R_{m,t_i}$. The reliability of the comparison star is checked by $R_{m,t_i} - C_{m,t_i}$.

**QVAR and differential photometry**

We have found the traditional method of performing differential photometry to be wasteful as it throws out other usable reference stars available in the field that can provide useful constraints to photometric accuracy. Our approach is to use all the available stars within a reasonable apparent brightness range as reference objects. To facilitate the use of many reference stars, Dr. Aidan O’Connor of the CIT Astrophysics group has designed a software programme called QVAR using the Interactive Data Language (IDL). QVAR is designed to look for variability in the object of scientific interest by comparing it to the average of a number of reference stars. It does this by first centring each star (including the object of interest, in this case an RQQ), i.e. subtracting the mean magnitude (across all frames) from the individual values. In this way, each star now has a mean magnitude of zero. For a given frame, the centred values for all the reference stars are averaged. Finally, the RQQ magnitude is compared with this average value for each frame. It is from this comparison that any decision on variability can be made by the user. The program also allows to search for night-to-night variability as the data may also be averaged over each night. All averages are weighted values, taking into account the individual error bars.

Individual reference stars can also be compared with the average of all
the other reference stars, to check whether they may themselves be variable. Individual data points and entire reference stars may be deleted from the analysis if necessary. Although this facility exists, we are very strict and reserved about removing data points and reference stars from the analysis. Data points are only deleted if, for example, there is a correlation with the presence of cosmic-rays in the stars’ PSF which results in that particular data point lying substantially off the mean value. A reference star is only removed if it is thought to be intrinsically variable, i.e. it displays structured variability rather than just scatter from the baseline that can not be accounted for. This of course is very rare; in all our datasets there have been only two instances where a star was removed due to intrinsic variability. One is the Cataclysmic Variable found in the PG 0804+761 field and the second one because it was discovered to be an unresolved double source in the field of PG1247+268.

Decisions on variability are made manually (by the user), but the probability that the data fit a (flat) straight line is estimated in QVAR, based on a chi-squared test.

2.6.3 Considerations for differential photometry

To determine the true nature of the variability in our sample of RQQS the following factors are also considered before arriving at the final DLCs.

Effects of non-linearity on the DLC

We have found that in 3 of our datasets (PG1821+643, V-band, La Palma 1996+1997 and PG1148-006, V-band, LaPalma 1997) that the sources approaching the non-linearity part of the CCD response functions can give rise to very convincing flare shapes of \( \approx 50 \) millimag in amplitude. To illustrate this we use only DLC for PG 1148-006. As can be seen from Figure 2.45 that the 5 data points in night two suggest the existence of impressive variability of \( \approx 50 \) millimag. This appears particular convincing because of the parabolic shape of the flare suggesting first a rise and then a decline in the RQQ luminosity. The reference stars appear very flat and display no suggestion of anything remotely like the variability seen in the RQQ. The flare in the DLC also follows the shape of the data points in the raw data for the RQQ. Only upon careful examination of the frames concerned it was
Figure 2.45: This shows the differential lightcurve of 148-006, V-band, La Palma, April 1997. The impressive flare present in r2 corresponds to the 5 RQQ data points just falling in the non-linear nse region of the CCD's performance.

revealed that these data points in the RQQ lie close to non-linear limit of the CCD.

We haven’t (as yet) performed any quantitative ais to show how much of the RQQ flux incident on the CCD lies withe non-linear response region and how significant this may be to the ov:alculation of an instrumental magnitude, but experimentally there is a ce point-to-point correspondence. Considering this correlation of non-linata points to the variability observed we can only conclude that it is the inearity of these data points that is most likely to be responsible for therved change in flux, rather than an intrinsic change in the RQQ’s luity. These data points are removed from our final DLCs. It is also impt to stress that, at these data points, the RQQ is not saturated and the of the RQQ appears sharp and narrowly peaked as it would be for br:ources observed during good photometric conditions.
Experimentally, we have also been able to correlate some of the one-off points that lie $\approx 30 - 60$ millimag off the mean that are present in the RQQ alone and not in any of the reference stars with non-linearity. While we would not consider one rogue point as evidence for variability, still one needs to be careful when claiming to see variability hinged on only one or two data points that appear off the mean.

Subtracting the d.c. bias level from the frames can take off $\approx 1K - 2K$ in pixel counts. Therefore it is important that frames are inspected for non-linearity before this type of processing is carried out since it would put any data points approaching non-linearity into the "safe" region. However, the response of the CCD would have been non-linear when the observations were made.

**Under estimation of IRAF error bars**

From our experience and other authors' reports (e.g. Gopal-Krishna et al., 1993a) we have found that the photometric errors calculated with the IRAF routines are under estimated. Gopal-Krishna et al. suggest that the formal errors returned by IRAF routines are too small by a factor of 1.75. We have generally found that the errors are more severely underestimated for brighter sources under better conditions than for fainter sources by looking at the scatter/dispersion from a (flat) line of our reference stars. We believe that the scatter in the reference stars (after removing any rogue points that may be accounted for, due to cosmic rays etc.), does provide the limit to the photometric accuracy as it is a direct measure of the experimental uncertainty. We have found that generally a multiplicative factor of $\approx 1.5$ is sufficient to iron out fluctuations within a given night. But this still leaves a dispersion of $\approx 30$ millimag on a night-to-night basis when averaged over each night. Therefore only night-to-night variability observed above the scatter in the reference stars is believed to be to intrinsic to the RQQ.

**Colour effects/extinction(2nd order and 3rd order)**

The second order differential extinction correction is the difference in extinction coefficients of the two stars, due to their different spectral energy distributions, multiplied by the whole airmass, (Young et al., 1991) or approximately

$$ (WRdC)M $$

(2.5)
where $R$ is the measure of atmospheric reddening, $W$ is proportional to the square of the optical bandwidth, $C$ is the colour index and $M$ is the airmass.

It is suggested (Carini 1990) that the differential photometry is unlikely to be affected by second order extinction effects or by the convolution of filter response with the spectral differences between the QSOs and stars because of the relatively small colour index differences. But Young (1974, 1988) suggests that these colour terms, which are often several hundredths of a magnitude, enjoy no cancelation in differential photometry, and can be a major source of error.

For most cases in our data sets the observations are taken using only one colour filter, therefore we can not directly check or correct for these colour effects. But using equation 2.5 we can get a feel for the approximate magnitudes of the errors that this may introduce. When using a V-band filter, $W_V = 0.03$, assuming a colour index, $B - V = 0.5$ for two objects, with $R = 0.1$ mag/airmass which is the difference between the extinction coefficients of two colours, $B$ and $V$ in this case, we get the difference in $V$ extinction of the two stars $= (0.03 \times 0.1 \times 0.5) = 1.5$ millimag/airmass. But the situation is worse when using a B-Band filter because $W_B = 0.26$, which gives the difference in $B$ extinction of the same two stars to be 13 millimag/airmass.

If the aerosol contents of the surrounding atmosphere changes then the atmospheric reddening, $R$ is also affected, e.g. if the aerosol extinction increases by 0.1 mag/airmass then the resulting increase in atmospheric $(B - V)$ reddening is about 0.02 mag/airmass and the difference in $B$ extinction of the same two stars will increase to 15.6 millimag. Observers often do differential photometry on nights of inferior transparency with relatively high and variable reddening and because second order effects depend directly on the reddening power, $R$ of the atmosphere, we can expect changes from night-to-night, even at fixed airmass (Young 1991). Therefore, the fluctuating weather conditions and the varying aerosol contents of the atmosphere may contribute to the scatter seen in sources from night-to-night if not corrected for. The effects due to changes in atmospheric reddening are systematic and therefore can not be reduced by averaging. The effects in U-band are much larger and in V-band they are about 8 times smaller (Young et al., 1991).

So, these effects will only significantly affect the measurements taken in the B-band in the present data set. Since, we’re using the extent of the scatter in the reference stars to limit our photometric accuracy, we have already indirectly included the contributions from these effects in the final
error estimates in the DLCs. As for future work it may be useful to take at least two/three observations in different photometric bands on each night to estimate colour indices of sources and to set limits on the change in the atmospheric reddening night-to-night.

**Cosmic rays**

Cosmic rays can be a real nuisance to astronomers using the aperture photometry technique. With the aid of the IRAF command IMEXAMINE it is possible to display areas covered by the source flux as surface plots and vector plots with the counts/pixel on one axis and pixel coordinates on the other. In such plots an incident cosmic-ray stands out as a sharp spike in the smooth Gaussian plot of the source. For the data presented here the frames were checked by such visual inspection for the presence of cosmic rays. By this method a cosmic ray within the sources PSF, is only detected if the counts per pixel are sufficiently larger than the counts per pixel resulting from the sources' flux. Therefore they can only reliably be picked out in the wings of the stellar flux distribution and less reliably so as you approach the central peak. This method is very time consuming and relies on the user to check every single frame and all the objects used for photometry, as well as the background within a given aperture for cosmic ray events.

We have found that cosmic-rays when incident within the RQQ’s PSF on the chip can give rise one-point fluctuations of the order of $\approx 30-60$ millimag in DLCs. Since, we are searching for amplitude fluctuations of the same order, it is important to remove any contributions to the photometry arising from cosmic rays. As yet there doesn’t exist an effective method within IRAF to deal with cosmic ray contributions to the photometry. An IRAF command IMEDIT can be used to remove some of these events, in particular those that are incident within the aperture from where the background is calculated. This is not a satisfactory method because it may also result in taking away source flux from the stellar wings, and can not be used to remove cosmic ray events incident within the object’s PSF.

In arriving at our final DLCs we removed any rogue data points that showed a correlation with the presence of cosmic ray events within the RQQ or reference star flux distribution.
Poor Tracking

Poor tracking/guiding can have the effect of smearing the object flux distributions on the CCD frame into ellipses, making a circular aperture ineffective in containing the "whole" flux. It was found that this can cause fluctuations of the order of $\approx 50$ millimag, and this can be very easily remedied by increasing the aperture size to contain "all" of the object's flux. The downside of this is that it leads to substantially larger error bars as more of the background sky pixels are included in the apertures used to calculate the instrumental magnitude. For studies like ours that look for small amplitude fluctuations, this reduces photometric accuracy and leads to a severe loss of resolution.

2.6.4 Arriving at the Final Lightcurve

1) The following checks are made to decide on the use of all the frames:
   (i) that there aren't any substantial gradients across the frames;
   (ii) there aren't any spurious structures in framing, for example from unwanted incident light, that may affect the photo;
   (iii) counts in sources are reasonably above the background level so that photometry can be performed to calculate instrumental magnitudes;
   (iv) counts in sources are within the linear regime of the CCD response function, and also that none of the selected sources saturated;
   (v) presence of cosmic rays that may affect the photo;
   (vi) trailing of objects, so that if necessary a larger aperture may be used;
   (vii) availability of good reference sources.

2) All frames to be reduced are flat-fielded, zeroed to remove any pixel-to-pixel variations and the additive d.c. level from the CCD respectively.

3) All the data is reduced using aperture photometry with the aid of PHOTMATE, which relies on using IRAF for HOT to perform the photometry.

4) DLCs for each RQQ are produced using QVA on average 4-7 objects used as references. An aperture of 14.0 pixels corresponding to 4.5" is used for majority of the RQQs with rare cases where a larger aperture is required.

5) The "under-estimated" IRAF error bars are set as a suitable value by inspecting the scatter in the reference stars.
6) Any rogue points believed to result from the factors mentioned above are removed from the analysis from the final DLCs.

7) Decisions on variability are made by visual inspection of DLCs and by using chi-squared test.

8) Averaged nightly lightcurves are also produced by using QVAR, this averages the datapoints within each night for all the objects and then the RQQ is compared with the reference stars in the same way as for the ordinary DLCs. This gain in integration time from averaging over all the observations per given night has the effect of reducing the errorbars. However, as for the ordinary DLCs, we look again to the scatter in the reference stars from night-to-night as the true estimate of the observational uncertainty. Again, variability decisions are based on comparing the RQQ with the observed scatter in the stars. Ideally, we should increase our errorbars to reflect the estimated uncertainty of the observations (from the reference scatter) in the averaged nightly DLCs, but for this thesis we have chosen to leave them as the errorbars directly produced by QVAR, to highlight that one needs to be cautious when interpreting such data in terms of variability because at first glance (i.e. not compared with the reference star scatter) most of our sources appear to show small magnitude variations on night-to-night timescales even after the under estimated IRAF error bars have been increased.
Chapter 3

Results and discussion

In this final chapter the results and conclusions from our investigation are presented.

3.1 Differential lightcurves

Here all the final DLCs and averaged nightly DLCs for all our sources are presented. All the DLCs have been produced using QVAR (for details please refer to section 2.6.2). The differential lightcurves showing nightly averages are also presented. It should be noted that the scales for the final DLCs are different to those for the lightcurves averaged over each night. Averaging the data points for each night to get a mean value reduces the size of the errorbars for that particular night, however we consider the scatter in the reference stars (also averaged over each night) as the true representation of the observational uncertainty from night-to-night. Therefore, at a first glance the averaged lightcurves may appear to show the source to be variable, but the source is only considered variable if the variability observed exceeds the reference star scatter. It should also be noted that while the time separation in hours within each night is representative of the time of observations from start to finish, it is not sequential over the entire observing period.
Figure 3.1: DLC for PG0003+199, V-band, La Palma, January, 1998.

Figure 3.2: Averaged nightly DLC for PG0003+199, V-band, La Palma, January, 1998.
Figure 3.3: DLC for PG0157+001, V-band, La Palma, January, 1998.

Figure 3.4: Averaged nightly DLC for PG0157+001, V-band, La Palma, January, 1998.
Figure 3.5: DLC for PG0804+761, V-band, La Palma, April, 1997.

Figure 3.6: Averaged nightly DLC for PG0804+761, V-band, La Palma, April, 1997. The night-to-night variations for the RQQ do not exceed the night-to-night reference star scatter hence the RQQ is not believed to be variable.
Figure 3.7: DLC for PG0804+761, V-band, La Palma, January, 1998.

Figure 3.8: Averaged nightly DLC for PG0804+761, V-band, La Palma, January, 1998.
Figure 3.9: DLC for PG0923+129, V-band, La Palma, January, 1998.

Figure 3.10: Averaged nightly DLC for PG09+129, V-band, La Palma, January, 1998.
Figure 3.11: DLC for PG0923+129, V-band, La Palma, May, 1999.

Figure 3.12: Averaged nightly DLC for PG091-129, V-band, La Palma, May, 1999.
Figure 3.13: DLC for PG1116+215, V-band, Calar Alto, June, 1996.

Figure 3.14: DLC for PG1116+215, V-band, La Palma, May/June, 1996.
Figure 3.15: Averaged nightly DLC for PG1116+215, V-band, La Palma, May/June, 1996.

Figure 3.16: DLC for PG1148-006, V-band, La Palma, April, 1997.
Figure 3.17: Averaged nightly DLC for PG1148-006, V-band, La Palma, April, 1997.

Figure 3.18: DLC for PG1148+549, V-band, La Palma, January, 1998.
Figure 3.19: Averaged nightly DLC for PG1148+549, V-band, La Palma, January, 1998.

Figure 3.20: DLC for PG1148+549, V-band, La Palma, May, 1999.
Figure 3.21: Averaged nightly DLC for PG18+549, V-band, La Palma, May, 1999.

Figure 3.22: DLC for PG1222+229, V-band, La Palma, April, 1997.
Figure 3.23: Averaged nightly DLC for PG1222+229, V-band, La Palma, April, 1997.

Figure 3.24: DLC for PG1247+268, V-band, La Palma, January, 1998.
Figure 3.25: Averaged nightly DLC for PG1247+268, V-band, La Palma, January, 1998.

Figure 3.26: DLC for PG1247+268, V-band, La Palma, May, 1999.
Figure 3.27: Averaged nightly DLC for PG1247+268, V-band, La Palma, May, 1999.

Figure 3.28: DLC for PG1334+248, V-band, La Palma, April, 1997.
Figure 3.29: Averaged nightly DLC for PG1334+246, V-band, La Palma, April 1997.

Figure 3.30: DLC for PG1334+246, V-band, La Palma, January, 1998.
Figure 3.31: DLC for PG1407+265, V-band, Calar Alto, June, 1996.

Figure 3.32: Averaged nightly DLC for PG1407+265, V-band, Calar Alto, June, 1996.
Figure 3.33: DLC for PG1407+265, V-band, La Palma, May/June, 1996.

Figure 3.34: Averaged nightly DLC for PG107+265, V-band, La Palma, May/June, 1996.
Figure 3.35: DLC for PG1407+265, V-band, La Palma, April, 1997.

Figure 3.36: Averaged nightly DLC for PG1407+265, V-band, La Palma, April, 1997.
Figure 3.37: DLC for PG1407+265, V-band, La Palma, May, 1999.

Figure 3.38: DLC for PG1416-129, V-band, Calar Alto, June, 1996.
Figure 3.39: Averaged nightly DLC for PG1416-129, V-band, Calar Alto, June, 1996.

Figure 3.40: DLC for PG1416-129, V-band, La Palma, April 1997.
Figure 3.41: Averaged nightly DLC for PG1416-129, V-band, La Palma, April, 1997.

Figure 3.42: DLC for PG1634+706, V-band, Calar Alto, June, 1996.
Figure 3.43: Averaged nightly DLC for PG1407+265, V-band, Calar Alto, June, 1996.

Figure 3.44: DLC for PG1634+706, V-band, La Palma, May/June, 1996.
Figure 3.45: Averaged nightly DLC for PG1634+706, V-band, La Palma, May/June, 1996.

Figure 3.46: DLC for PG1634+706, V-band, La Palma, April, 1997.
Figure 3.47: Averaged nightly DLC for PG1634+706, V-band, La Palma, April, 1997.

Figure 3.48: DLC for PG1634+706, B-band, La Palma, May, 1998.
Figure 3.49: Averaged nightly DLC for PG1634+706, B-band, La Palma, May, 1998.

Figure 3.50: DLC for PG1634+706, R-band, La Palma, May, 1998.
Figure 3.51: Averaged nightly DLC for PG1634+706, R-band, La Palma, May, 1998.

Figure 3.52: DLC for PG1634+706, B-band, La Palma, May, 1999.
Figure 3.53: DLC for PG1634+706, R-band, La Palma, May, 1999.

Figure 3.54: DLC for PG1634+706, V-band, La Palma, May, 1999.
Figure 3.55: DLC for E1821+643, V-band, Calar Alto, June, 1996.

Figure 3.56: Averaged nightly DLC for E1821+643, V-band, Calar Alto, June, 1996.
Differential lightcurve for E1821+643, V-band, La Palma May/June 1996

Figure 3.57: DLC for E1821+643, V-band, La Palma, May/June, 1996.

Averaged nightly differential lightcurve for E1821+643, V-band, La Palma May/June 1996.

Figure 3.58: Averaged nightly DLC for E1821+643, V-band, La Palma, May/June, 1996.
Figure 3.59: DLC for E1821+643, V-band, La Palma, April, 1997.

Figure 3.60: Averaged nightly DLC for E1821+643, V-band, La Palma, April, 1997.
Figure 3.61: DLC for E1821+643, B-band, La Palma, May, 1998.

Figure 3.62: Averaged nightly DLC for E1821+643, B-band, La Palma, May, 1998.
Figure 3.63: DLC for E1821+643, R-band, La Palma, May, 1998.

Figure 3.64: Averaged nightly DLC for E1821+643, R-band, La Palma, May, 1998.
Figure 3.65: DLC for E1821+643, B-band, La Palma, May, 1999.

Figure 3.66: DLC for E1821+643, R-band, La Palma, May, 1999.
Figure 3.67: DLC for E1821+643, V-band, La Palma, May, 1999.

Figure 3.68: DLC for PG2112+059, V-band, Calar Alto, June, 1996.
Figure 3.69: Averaged nightly DLC for PG2112+059, V-band, Calar Alto, June, 1996.

Figure 3.70: DLC for PG2112+059, V-band, La Palma, May/June, 1996.
Figure 3.71: Averaged nightly DLC for PG2112+059, V-band, La Palma, May/June, 1996.
3.1.1 PG 0003+199

The lightcurve for PG 0003+199 is shown in figure 3.1. This was observed in January 1998 in La Palma. The field containing this data is quite sparse and hence only 4 good reference stars were available for data reduction. Star 4 was removed from the analysis as it was found to unsteady and it didn't flatten out even after the error bars were increased by a factor of two. The first four data points were also removed from all sources due to trailing. Figure 3.1 shows our best estimate of the behaviour of this object. We find that PG0003+199 shows evidence of night-to-night variability (figure 3.2) of $\approx 25$ millimag considering that there no such behaviour is seen in the reference stars over night-to-night.

3.1.2 PG 0157+001

Figure 3.3 shows our best estimate of the DLC for PG0157+001. In this field, only four good references were available. This was observed over three nights in January 1998. Night three is removed from the DLC because comparison with each of the stars gives rise to a different pattern of behaviour, hence we feel that nothing really can be concluded about the RQQ's behaviour on night three from our present data set. On the two nights shown, (figure 3.4) the DLC is flat within the errorbars.

3.1.3 PG 0804+761

Figure 3.5 and Figure 3.8 show the DLCs for PG0804+761 observed in January 1998 and April 1997 respectively. This is quite a good field for differential photometry as it has 6 stars comparable to the RQQ in apparent brightness. Stars 4 and 3 were removed from the January 1998 and April 1997 datasets respectively, because this particular star is believed to be a cataclysmic variable and shows some very impressive flares in both our data sets. The 1st point in the April 1997 DLC,which sat at $\approx 0.03\text{mag}$, has been removed because the CCD counts were in the non-linear region and the 26th point in the same data set was also removed as a trail of cosmic rays was observed to be coincident within the RQQ PSF. No evidence for variability, above that of the scatter in reference stars is observed in either data set.
3.1.4  PG 0923+129

Figures 3.9 to 3.12 show the DLCs for this RQQ as observed in January 1998 and May 1999 respectively. This is a rich field with lots of stars and galaxies and the shell galaxy around the nucleus is very prominent. For January 1998 data the IRAF errorbars (for all objects) were increased by a scale factor of 1.5 to flatten out the reference stars. Even with this we found the data was erratic; we removed stars 1, 4 and 5 and this left only two stars in the final DLC. For the May 1999 data there were only 2 stars available in the field as the observing conditions poor. There is no indication of either intra-day or night-to-night variability in either data sets.

3.1.5  PG 1116+215

Figures 3.13 to 3.15 show the DLCs for PG1116+215 form La Palma 1996 and Calar Alto 1996 data sets respectively. The number of data points is very small for this RQQ, especially as the Calar Alto data has only one data point per night. This should be noted when drawing any conclusion about the RQQ’s behaviour based on the present observations. Currently, with the available observations, there isn’t any evidence to suggest variability.

3.1.6  PG 1148-006

Figures 3.16 and 3.17 show the final DLCs for this RQQ and it is produced using 7 reference stars. Seven non-linear data points have also been removed from the DLC. No evidence for variability is present in the DLC, but once again there are too few usable observations to describe the RQQ behaviour.

3.1.7  PG 1148+549

DLCs for La Palma January 1998 and May 1999 are shown in figures 3.18 to 3.21. There is no evidence for any intra-day variations, in either DLC. The magnitude of the scatter in the reference stars from night-to-night is the same as the RQQ, therefore, implying that the RQQ is not variable at this timescale within the limits of photometric accuracy.
3.1.8 PG 1222+229

This RQQ was observed once in April 1997 in La Palma and figures 3.22 and 3.23 show the final DLCs. Three reference stars are used in the analysis of the data. Frame 6 is removed from the DLC as it may be influenced by a cosmic ray incident in the RQQ PSF. The second frame on the night of 09/04/97 lies $\approx 30$ millimag below the rest. Although we're not able to find an adequate extrinsic explanation for it to lie off the mean, we do not believe that this represents a rapid event for the RQQ because it is also present in some of the other reference stars. We note that there is a slight brightening trend shown in the night of the 11/04/97, but overall there isn’t substantial evidence to suggest variability on IDV or night-to-night timescales.

3.1.9 PG 1247+268

Figures 3.24 to 3.27 show the DLCs for this RQQ for La Palma January 1998, and La Palma, May 1999, respectively. Star one from the 1998 analysis was removed because it is a double source leaving three stars as references for the final DLC. As seen from figure 3.25 there is a very slight hint of variability in the night of 07/01/98 but it is not at all convincing when the RQQ is compared with just one reference star at a time. Neither of the DLCs suggest that this source showed any variability within a night or on night-to-night timescales.

3.1.10 PG 1334+246

Although this was observed in two observing runs there are very few data points, too few in fact to say anything substantial about this RQQ’s IDV or night-to-night variability properties. In the DLCs shown in figures 3.28 to 3.30 it can be seen that there is no evidence to suggest that the RQQ is variable on these timescales.

3.1.11 PG 1407+265

Figures 3.31 to 3.37 show the final DLCs for this RQQ. There is no evidence for IDV or night-to-night variability in any of the DLCs.
3.1.12   PG 1416-129

Figures 3.40 and 3.41 show the final DLCs for April 1997 and the figures 3.38 and 3.39 show the final DLCs for Calar Alto 1996. From the 1997 analysis, star six was removed as it contained 2 data points that were well off the general trend. The iraf error bars were increased by a factor of 1.5. There is no evidence from the present data to suggest that this RQQ is variable.

3.1.13   PG 1426+015

There are only four datapoints for this RQQ and the DLC is flat.

3.1.14   PG 1634+706

PG 1634+706 has been observed extensively in all our RQQ campaigns. Figures 3.42 to 3.54 show the final DLCs.

May 1999 campaign

The RQQ was observed in B, R and V bands and no variability is seen but this can only be treated as a comment considering that there aren’t enough data points for IDV type analysis.

May 1998 campaign

The RQQ was observed in B and R bands. From the B-Band data four data points from star two were removed, because they were too close to the edge on the CCD frame. There is a hint of very marginal night-to-night variability in the B-band data of $\approx 20$ millimag compared to the scatter of $\approx 10$ millimag in the reference stars. But there is no suggestion of this slight trend in the R band data and there is no evidence to suggest IDV in either band.

April 1997 Campaign

The RQQ was observed in V-band only. The IRAF error bars were increased by a factor of 1.5. Figures 1.44 and 1.45 show that the RQQ is not variable at either IDV or on night-to-night timescales for this data set.
May/June 1996

The RQQ was observed in V-band for this campaign. Again the IRAF error bars were increased by a factor of 1.5. The DLC seen in figure 3.42 shows that the RQQ is flat with the given errorbars.

Calar Alto 1996 campaign

The IRAF error bars were increased by a factor of 1.5 and stars 2 and 6 as shown in the finding charts were removed from analysis leaving four stars as references for the final DLC. Again, no evidence for IDV or night-to-night variability is seen in the DLC for these observations.

3.1.15 PG 1821+643

RQQ E1821+643 has been observed the most extensively in all our campaigns. The final DLCs are shown in figures 3.55 to 3.67.

May 1999

E1821+643 is in a very rich field with plenty of stars available as references. It was observed in B, R, and V bands but there are only few data points per bandwidth and no evidence of variability was seen in any band.

May 1998

In May 1998 E1821+643 was observed extensively in both B and R bands. No evidence for variability was observed in either band.

April 1997

E1821+643 was observed in the V-band over six nights. The IRAF errorbars are scaled up by a factor of 1.5. Originally, the lightcurve showed a 0.05 mag flare but this structure was discovered to arise due to CCD non-linearity. After the nonlinear points are removed from the final DLC (figure 3.59) there is no indication of any variability in the source.
May/June 1996

Again, observations were taken in the V-band and the IRAF errorbars are scaled up by a factor of 2.0 to flatten out the reference stars. The following frames are removed from the final DLC: frames 12, 13 and 14 because they were mistakenly taken in the wrong filter; frames 9 and 10 due to very low flux values; frame 7 due to a cosmic ray incident in the RQQ PSF; frame 8 due to smearing and frames 17, 18, 42-46 due to non-linearity. There is interesting night to night behaviour but nothing sufficiently convincing.

Calar Alto, June 1996

IRAF error bars are increased by a scale factor of 2.0. Eight reference stars are used to produce the final DLC and again no interesting variations above that of reference star scatter are observed.

3.1.16 PG 2112+059

Figures 3.68 to 3.71 and show the DLCs for this source. For both observing epochs the IRAF error bars have been scaled up by a factor of 1.5. No variability is observed during either observing period.

3.2 Blazar events versus the RQQ sample

We took a sample of ten blazar ROV events and calculated the expected flare amplitudes for the RQQs in our sample, corresponding to the luminosity change observed for each blazar event. We wanted to consider whether the typical ROV events that are reported in blazars would be observable in our sample. In general, based on the analysis of the scatter in our datasets we consider that our detection threshold lies \( \approx 40 - 50 \) millimag as a conservative estimate, i.e. we consider, that is the limit for the photometric accuracy achievable for our current observational data. We would be confident of the reality of any events only if observed magnitudes were above this threshold. Therefore, only flare amplitudes above \( \approx 50 \) millimag are considered detectable for this exercise. Ten blazar events were calculated to ascertain whether the expected amplitudes would fall above this threshold.

The expected flare amplitudes (magnitudes) are calculated in the following manner: First, we calculated the quiescent luminosity, \( L_{s1} \), for the
first source (1 of the 10 blazars) and then its luminosity at the flare peak, \( L(s1)_{\text{flare}} \). Following this we calculated what size flare, in magnitudes, this luminosity change would correspond to in the second source (a RQQ from our sample). For these calculations the values for the deceleration parameter, \( q_0 = 0.5 \), and the Hubble constant, \( H = 75kms^{-1}Mpc^{-1} \) are used. If \( m_{s1} \) is the quiescent apparent magnitude of the first source and \( \delta m_{s1} \) is the magnitude of the observed flare in the first source then

\[
m_{s1}(f) = m_{s1} - \delta m_{s1} \tag{3.1}
\]

where \( m_{s1}(f) \) is the magnitude of the first source at the flare peak. Using equations 3.2 to 3.5, \( L(s1)_{q} \) is calculated:

\[
L(s1)_{q} = F(s1)_{q}4\pi D^2 \tag{3.2}
\]

where \( D \) is given by

\[
D = d_{s1} \times 3.086 \times 10^{24} \tag{3.3}
\]

and \( d_{s1} \) is the \textit{luminosity distance} for the first source given by

\[
d_{s1} = 3 \times 10^5 z / H (1 + z (1 - q_0 / \sqrt{1 + 2zq_0 + 1 + q_0 z})) \tag{3.4}
\]

where \( z \) is the redshift of the first source. The quiescent flux for the first source, \( F(s1)_{q} \) is

\[
F(s1)_{q} = F/2.512^{m_{s1}} \tag{3.5}
\]

where \( F = 7.056 \times 10^{-6} \). Now the flux of the first source at the flare peak is simply

\[
F(s1)_{\text{flare}} = F/2.512^{m_{s1}(f)} \tag{3.6}
\]

and the luminosity of the first source at flare peak is

\[
L(s1)_{\text{flare}} = F(s1)_{\text{flare}}4\pi D^2 \tag{3.7}
\]

and hence the luminosity change caused by the flare is

\[
L_{\text{flare}} = L(s1)_{\text{flare}} - L(s1)_{q} \tag{3.8}
\]

The quiescent luminosity of the second source \( L(s2)_{q} \) is calculated as above. Then the luminosity of the second source at flare peak is

\[
L(s2)_{\text{flare}} = L(s2)_{q} + L_{\text{flare}} \tag{3.9}
\]
Given that flux of the second source at flare peak is

\[ F(s2)_{\text{flare}} = L(s2)_{\text{flare}}/4\pi D(2)^2 \]  

(3.10)

and by rearranging the general form of equation 3.6, the apparent magnitude at flare peak of the second source is calculated and subtracting this from the quiescent apparent magnitude gives the expected flare amplitude for the second source.

Figure 3.72 shows the number of the blazar events that would lie above the detection threshold for each RQQ in the sample. It shows that if luminosity changes comparable to those observed in most blazars were taking place in RQQs we should certainly be able to detect them optically except in our most luminous and high redshift RQQs.

The duty cycle for these blazar events is very high, according to Carini et al. (1990) if such a source is observed for over 8 hours the the probability of seeing significant ROV is \( \approx 80\% \) and as a large number of RQQs in our sample have been observed for several hours over many nights these events, if they were common place in RQQs, would also have had a high probability of detection. We note that the number of blazars considered is only ten, and one would have to consider a much larger sample of blazar events to increase the validity of this statement, but it is nevertheless an interesting indication that our RQQ sample does behave differently to a typical sample of RLQs.

### 3.3 Radio quiet quasars from the Bright Quasar Survey (BQS)

Here we consider a flare of amplitude 0.05 mag as observed in E1821+643 which was previously thought to be genuine and now attributed to CCD non-linearity. We took the 68 RQQs from the BQS to see what flare amplitudes may be expected in these objects resulting from the luminosity change corresponding to the 0.05 mag change in E1821+643. We found that for 65% of the BQS RQQs the expected amplitudes would be substantially larger than 0.05 mag and hence would be detectable (see figure 3.73).
Figure 3.72: Histogram showing the number of RQQs from our sample with detectable (above 0.05 mag) flare amplitudes corresponding to the observed luminosity changes in the blazar sample.
Figure 3.73: Histogram displaying the expected flare amplitudes in the BQS RQQs corresponding to the luminosity change observed for a 0.05 mag flare (due to CCD non-linearity) observed in E1821+643.
3.4 Micro-magnitude photometry

As mentioned above we estimate that 0.05 mag is our detection threshold. Therefore, we looked to see what luminosity changes correspond to this detection threshold in sources of different absolute magnitudes. The results of this are summarised in Table 3.1. It is clear that with the photometric accuracies currently attainable it is possible to observe only the very powerful events. For the very luminous quasars in the sample, the blazars events which correspond to large luminosity changes ($\approx 10^{43}$ to $10^{45}$ ergs$^{-1}$) lie well below the detection level at $\approx 100\mu$mag. The very large accretion disks associated with our objects essentially radiate like a blackbody and are very luminous at optical wavebands. Therefore, it is possible for the disk to obscure the hypothetical jets from detection in the optical because of contrast effects. This would suggest that we are more likely to find evidence of ROV, and hence possible evidence of weak jets (constrained by observational accuracy currently obtainable), in the less luminous flat-spectrum, core-dominated RQQs. We need to look at wavelengths where the disk isn't so luminous that contrast effects completely drown out the weak jet.

3.5 The shifted synchrotron peak?

It is hypothesised, as already noted, that the electrons in a jet emit mainly by synchrotron and inverse compton and as the electrons are ejected with higher energies the peak emission wavelength also gets shorter. It has been suggested by Ghisellini et al. (1998) that there exists a possible family of objects in which the synchrotron peak has been shifted to extremely short wavelengths, i.e., the peak occurs at hard x-ray or even $\gamma$-ray wavelengths rather, than in the optical or at centimeter wavelengths. PG 1416-129 (Staubert & Maissack 1996), PG 1334+246 (Brinkman et al., 1996) and PHL 1092 (Brandt et al., 1999) have been reported as being rapidly variable in the x-ray. But so far have shown no evidence of ROV. So, these sources may represent members of the RQQ population where the synchrotron peak has been shifted to x-ray wavelengths.

An intriguing possibility is that these sources contain an accretion disk which dominates in the optical but a jet with a synchrotron peak in the x-ray regime. So, we may have a better chance of finding signatures of a weak relativistic jet at these shorter wavelengths where the accretion disk is not
Table 3.1: Table showing the expected luminosity changes at the detection threshold of 0.05 mag for our RQQ sample (column 2) and these expected luminosities compared with the total optical luminosity of the Milky Way (column 3).

<table>
<thead>
<tr>
<th>Name of RQQ</th>
<th>$\delta L$ for a 0.05 mag event (ergs s$^{-1}$)</th>
<th>$\delta L/L_{Milkyway}$ (ergs s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG0003+199</td>
<td>$1.3 \times 10^{42}$</td>
<td>0.06</td>
</tr>
<tr>
<td>PG0157+001</td>
<td>$6.4 \times 10^{42}$</td>
<td>0.3</td>
</tr>
<tr>
<td>PG0804+761</td>
<td>$5.8 \times 10^{42}$</td>
<td>0.2</td>
</tr>
<tr>
<td>PG0903+129</td>
<td>$5.8 \times 10^{41}$</td>
<td>0.03</td>
</tr>
<tr>
<td>PG1116+215</td>
<td>$1.8 \times 10^{43}$</td>
<td>0.8</td>
</tr>
<tr>
<td>PG1148-006</td>
<td>$4.2 \times 10^{44}$</td>
<td>1.9</td>
</tr>
<tr>
<td>PG1148+549</td>
<td>$3.8 \times 10^{44}$</td>
<td>17.2</td>
</tr>
<tr>
<td>PG1222+229</td>
<td>$2.7 \times 10^{45}$</td>
<td>122.7</td>
</tr>
<tr>
<td>PG1247+268</td>
<td>$2.6 \times 10^{45}$</td>
<td>118.2</td>
</tr>
<tr>
<td>PG1334+246</td>
<td>$7.8 \times 10^{42}$</td>
<td>0.35</td>
</tr>
<tr>
<td>PG1407+265</td>
<td>$3.9 \times 10^{44}$</td>
<td>17.7</td>
</tr>
<tr>
<td>PG1416-129</td>
<td>$7.8 \times 10^{42}$</td>
<td>0.35</td>
</tr>
<tr>
<td>PG1426+015</td>
<td>$2.6 \times 10^{42}$</td>
<td>0.12</td>
</tr>
<tr>
<td>PG1634+706</td>
<td>$1.8 \times 10^{45}$</td>
<td>81.8</td>
</tr>
<tr>
<td>E1821+643</td>
<td>$1.5 \times 10^{44}$</td>
<td>6.8</td>
</tr>
<tr>
<td>PG2112+059</td>
<td>$7.6 \times 10^{43}$</td>
<td>3.5</td>
</tr>
</tbody>
</table>

very dominant. However, this may also prove to be a difficult endeavour as the sensitivity that is currently available at x-ray wavelengths may not be adequate to detect small amplitude fluctuations.

3.6 Conclusion

In this thesis, 16 RQQs with flat or inverted spectra and compact cores have been observed in the optical to search for ROV. The presence of such variability events in RLQs (especially blazars) is thought to be closely linked to the existence of a relativistic jet. The conclusions that are drawn from this work are as follows:

- The errorbars associated with the magnitudes calculated by the IRAF phot routine are generally underestimated by a factor of $\approx 1.5$.  

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• There is, in general, a systematic scatter of \( \approx 30-50 \) millimag from night-to-night observed in the reference stars. Our photometry is limited to that detection threshold even though within a given night the error bars can be as small as \( \approx 5-10 \) millimag.

• Counts approaching the non-linear region of the CCD's performance (well below the saturation limit) can produce spurious, but impressive flares of \( \approx 50-80 \) millimag.

• We find marginal evidence of variability on a night-to-night timescale of \( \approx 30 \) millimag in PG0003-199 in January 1998. We conclude that the observed variability in this source is considerably larger than the scatter seen in the reference stars from night-to-night.

The other 15 RQQs in our sample do not show any evidence of variability either on IDV or on night-to-night timescales in the V-band. We also found no evidence of variability in B or R bands for the RQQs E1821+643 and PG1634+706 even though these sources were monitored extensively. (There are \( \approx 200 \) datapoints spanning a period of 5 nights for each band for E 1821+643 and \( \approx 70 \) datapoints in each band for PG 1634+706).

• We find from an analysis of the ROV events in 10 blazars that if the luminosity changes of the same order were taking place in our sample, we would be able to detect them in most objects except the most luminous (PG 1222+229, PG 1247+268 and PG 1634+706) where only one of the blazar events sits marginally above the detection threshold of \( \approx 50 \) millimag.

• The non-linearity induced flare in E1821+643 of \( \approx 50 \) millimag would be manifested as a much larger amplitude change in about 65% of the RQQs in the BQS, making such luminosity changes easily detectable. The lack of any such changes argues against powerful jets in the BQS RQQ sample. We also find that events above the detection threshold of \( \approx 50 \) millimag would correspond to very large changes in luminosity and this significantly constrains the models that can be tested with optical variability studies.

We started this investigation with the premise that RQQs may harbour weak jets. We investigated 16 RQQs for evidence of ROV, as the existence of such
behaviour (as seen in many RLQs) is thought to be an important tool by which one can constrain and perhaps discriminate between the different models proposed for AGN variability. The lack of observed variability we find is not necessarily an indication that these sources do not harbour weak jets. Instead we find the photometric accuracy attainable at present may be a limiting factor as far as an investigation of this nature is concerned. Photometry at the milli or preferably micro magnitude level is required to find blazar type ROV but from a jet which may be weaker by factors of $\approx 10^2 - 10^3$ as compared to blazar jets. This type of accuracy is not currently feasible. Atmospheric and instrumental effects can easily increase the errors to a few tens of millimagnitudes. Also, in the optical one is always competing against the dominant, very luminous, accretion disk at optical wavelengths and therefore, perhaps an investigation into x-ray or $\gamma$-ray variability properties may prove to be a more fruitful tool to search for signatures of a weak jets in RQQs.
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