Optical variability of radio-luminous palomar-green quasars

Diane Eggers
University of Nevada, Las Vegas

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OPTICAL VARIABILITY OF RADIO-LUMINOUS

PALOMAR-GREEN

QUASARS

by

Diane Eggers

Bachelor of Science
University of Minnesota
1990

A thesis submitted in partial fulfillment
of the requirements for the degree of

Master of Science

in

Physics

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University of Nevada, Las Vegas
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Diane Eggers

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Examination Committee Chair

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ABSTRACT

Optical Variability of Radio-Luminous Palomar-Green Quasars

by

Diane Eggers

Dr. Donna Weistrop, Examination Committee Chair
Professor of Physics
University of Nevada, Las Vegas

The goal of this project is to test the shocked jet model for quasar variability at optical wavelengths. The ten quasars with the highest radio core luminosity at 5 GHz in the Palomar Bright Quasar Survey were selected for this monitoring program.

Seven out of the ten radio-luminous quasars exhibited signs of short-term variability, and all ten radio-luminous quasars showed signs of long-term variability. We assume our QSO cores have high radio luminosities because they have a jet of relativistic material aligned close to our line-of-sight; we would then expect to see more variability than in a sample of radio-quiet QSOs if the shock in the jet is the cause of variability. There is evidence that our radio-loud QSOs are more likely to have short-term variations compared to samples of radio-quiet QSOs. This finding supports the model of QSO variability being caused by shock waves in the relativistic plasma jet.
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CHAPTER 1

INTRODUCTION

Discovery of Quasars

The word *quasar* originated from the term "quasi-stellar radio source". In 1962, radio astronomers used occultations by the moon to identify the optical counterpart of a radio source named 3C 273 (object 273 in the Third Cambridge Catalogue of radio sources). The optical counterpart of 3C 273 could not be identified with the optical telescopes of the time due to the poor spatial resolution of the radio telescopes. Therefore, it took the lunar occultation method to pinpoint its location accurately. The optical source turned out to be a 13th magnitude star-like object, and was thus referred to as a "quasi-stellar radio source", or quasar. At that time no stars other than our sun were known to be radio sources, and the sun's radio emission is detectable due only to its close proximity. The optical spectrum of 3C 273 showed emission lines that could not be identified. In 1963, Maarten Schmidt recognized the pattern of hydrogen Balmer lines in 3C 273's spectrum, except the lines were greatly redshifted, indicating the object was not a star located in our galaxy. Since then more quasars have been discovered, although not all are "radio-loud". Radio-loud is defined as $R \geq 10$, where $R$ is the ratio of total flux density in millijanskys at 6 cm wavelength to optical flux density at an effective observed wavelength of 4400 Å (Kellermann et al. 1989, and Kellermann et al. 1994). A jansky (Jy) is equal to $10^{-26}$ W m$^{-2}$ Hz$^{-1}$. All objects that appear star-like and have broad, highly
redshifted emission lines, whether they have strong radio emission or not, are classified as "quasi-stellar objects", or QSOs.

**The Theory Behind Active Galactic Nuclei**

We now consider QSOs to be a type of active galaxy—one that is emitting unusually large amounts of energy as compared to a normal galaxy. Active galaxies are also referred to as Active Galactic Nuclei (AGN), since there appears to be a central engine in the nucleus that is driving the active galaxy phenomenon. Other types of AGNs include Seyfert 1 and 2s, broad- and narrow-line radio galaxies, and BL Lacertae objects. Most QSOs appear star-like, and all exhibit strong, broad, and redshifted emission lines. In addition, some QSOs display the following characteristics: high contrast of brightness between the nucleus and the rest of the host galaxy (if the host galaxy can be resolved), explosive appearance or jet-like protuberances, and a small region of variability in the nucleus. Continuum radio emission from radio-loud QSOs is dominated by nonthermal or synchrotron emission (i.e., emission that is not emitted by stars) (Bregman 1993).

There is a unified model that is currently used to describe all of the AGNs; which type of AGN is seen depends on the orientation of the model with respect to the observer and the relative luminosity of the nucleus to the rest of the galaxy. There also seems to be a morphological dependence; Seyfert galaxies seem to be mostly spirals, while radio galaxies are mostly ellipticals. QSOs are the rarest and most luminous AGNs. Radio-loud QSOs are extensions of broad-line radio galaxies to high optical luminosity, and radio-quiet QSOs are at the luminous end of Seyfert 1 galaxies (Osterbrock 1989) with $M_B < -23$ mag.
In the nucleus of the QSO, the central engine is presumably powered by a supermassive black hole. This is believed to be the case due to the high luminosities observed—luminosities too high for a stellar source. Stars must satisfy the Eddington limit, which specifies the maximum possible luminosity that a spherically symmetric object can have in order for it to remain stable. Higher luminosities result in the radiation pressure overcoming gravitational forces and the object is ripped apart (Osterbrock 1989). The Eddington limit, therefore, gives a lower limit to the mass of the object. The Eddington limit is as follows

\begin{equation}
L \leq L_E = \frac{4\pi G m_H M}{\sigma_T} = 1.26 \times 10^{38} \frac{M}{M_{\text{solar}}}
\end{equation}

where \( L \) is luminosity in erg s\(^{-1}\), \( L_E \) is the Eddington luminosity in erg s\(^{-1}\), \( G \) is the gravitational constant, \( \sigma_T \) is the electron-scattering cross section, \( m_H \) is the mass of a hydrogen atom, \( M \) is mass of the object, and \( M_{\text{solar}} \) is one solar mass. This equation can be rewritten

\begin{equation}
\frac{L}{L_{\text{solar}}} \leq \frac{L_E}{L_{\text{solar}}} = 3.22 \times 10^4 \frac{M}{M_{\text{solar}}}
\end{equation}

Using Eqn 2, we see that for typical AGN luminosities of \( L = 10^{12} \, L_{\text{solar}} \), the central source must have \( M \geq 3 \times 10^7 M_{\text{solar}} \). Since the most massive, stable stars are on the order of \( 10^2 M_{\text{solar}} \), the central source cannot be a single star. A constraint on the size of the
central source is the observed continuum variability. The continuum cannot vary substantially faster than it takes light to cross the central source. QSOs have been observed to vary at optical wavelengths within the course of a single night (Jang & Miller 1997), suggesting sizes of the central sources on the order of a lightday. We cannot totally exclude the possibility that the central source could be a very dense cluster of stars. However, since the central source is approximately $10^8 \ M_{\odot}$, the cluster would need to consist of one million of the most massive stars within a volume a few light days across. Since the central source is contained within such a small volume and is capable of producing large luminosities, a more promising explanation for the central source is the release of gravitational potential energy from material in an accretion disk falling onto a supermassive black hole. Highly collimated jets of relativistic particles are ejected, probably along the rotational axis of the accretion disk. These jets are closely related to activity in the inner accretion disk (Eikenberry et al. 1998). QSO cores that are radio-loud are thought to be so because they have a relativistic jet pointed toward us.

**Variability Models**

There are two prominent theories which may explain the variability of AGNs. One theory is that there are flares or hot spots in the accretion disk that produce variability. The second theory is that the variability is caused by shock waves propagating down the relativistic jet (Jang & Miller 1995). The shock waves are produced by disturbances in the flow of particles in the jet. As the relativistic electrons pass through the shock front, they are heated and accelerated, which results in an increase in brightness (Marscher & Gear 1992). There is also an increase of synchrotron radiation because the magnetic field lines are compressed by the shock wave (Bregman 1993).
The reason variability is of interest is twofold. First, the time scales of the
variations give us an idea of the size of the structures near the center of AGNs. Secondly,
observations of the variability help construct a model for QSOs. According to one
model, if a QSO is radio-loud, its jet is pointed toward us, and if the variability arises
within the jet, the QSO should show some signs of variability. If it doesn't show
variability, then either the shocked jet model is incorrect and the variability is not caused
by the jets, or we are not looking down the jet and the QSO is radio-loud for some other
reason. Studying QSOs may lead to understanding galaxy evolution in general, since
observations suggest that most galaxies have gone through a quasar phase in their youth
(Kormendy & Richstone 1995).

To test the shock in the jet model, a monitoring program was established to look
for both short- and long-term optical variability in radio-loud QSOs. Short-term is
defined as variability within a single night or between consecutive nights. Long-term
denotes variability over a time span of longer than three months.
CHAPTER 2

THE SAMPLE

Our sample consists of the ten QSOs with the highest radio core luminosity (as measured by Kellermann et al. 1989) at 5 GHz in the Palomar Bright Quasar Survey (BQS). The BQS includes 114 objects to an average limiting magnitude of B=16.16 and covers an area of over 10,714 deg$^2$ on the sky. There are 92 QSOs with $M_b<-23$ mag in the BQS (Schmidt & Green 1983). Since our sample QSOs are a subset of the BQS, they are bright at optical wavelengths and therefore suitable for optical monitoring with a modest telescope. Refer to Table 1 for a description of the sample.

Table 1. The Sample of Radio-Luminous PG QSOs

<table>
<thead>
<tr>
<th>QSO</th>
<th>RA (hms)</th>
<th>DEC (dms)</th>
<th>z</th>
<th>Measured Core Flux Density (mJy)</th>
<th>Luminosity (W Hz$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0003+158</td>
<td>00 05 59.2</td>
<td>+16 09 49</td>
<td>0.45</td>
<td>130</td>
<td>$8.68 \times 10^{23}$</td>
</tr>
<tr>
<td>1103-006</td>
<td>11 06 31.8</td>
<td>-00 52 52</td>
<td>0.425</td>
<td>76</td>
<td>$4.41 \times 10^{25}$</td>
</tr>
<tr>
<td>1222+228</td>
<td>12 25 27.4</td>
<td>+22 35 13</td>
<td>2.046</td>
<td>11</td>
<td>$4.32 \times 10^{26}$</td>
</tr>
<tr>
<td>1226+023</td>
<td>12 29 06.7</td>
<td>+02 03 08</td>
<td>0.158</td>
<td>26400</td>
<td>$1.56 \times 10^{27}$</td>
</tr>
<tr>
<td>1241+176</td>
<td>12 44 10.8</td>
<td>+17 21 04</td>
<td>1.273</td>
<td>130</td>
<td>$1.32 \times 10^{27}$</td>
</tr>
<tr>
<td>1302-102</td>
<td>13 05 33.1</td>
<td>-10 33 20</td>
<td>0.286</td>
<td>780</td>
<td>$1.77 \times 10^{26}$</td>
</tr>
<tr>
<td>1538+477</td>
<td>15 39 34.8</td>
<td>+47 35 31</td>
<td>0.773</td>
<td>19</td>
<td>$5.00 \times 10^{25}$</td>
</tr>
<tr>
<td>1718+481</td>
<td>17 19 38.2</td>
<td>+48 04 12</td>
<td>1.084</td>
<td>104</td>
<td>$6.77 \times 10^{26}$</td>
</tr>
<tr>
<td>2308+098</td>
<td>23 11 17.7</td>
<td>+10 08 16</td>
<td>0.432</td>
<td>87</td>
<td>$5.26 \times 10^{25}$</td>
</tr>
<tr>
<td>2344+092</td>
<td>23 46 36.8</td>
<td>+09 30 46</td>
<td>0.677</td>
<td>1700</td>
<td>$3.17 \times 10^{27}$</td>
</tr>
</tbody>
</table>
The first column lists the designation for the QSOs, also referred to as Palomar-Green (PG) objects, and the next two columns list the right ascension (RA) in hours, minutes, and seconds, and declination (DEC) in degrees, minutes, and seconds of the QSOs in epoch 2000 coordinates. Columns 4 and 5 list redshift and the measured core flux density in millijanskys at $5\, \text{GHz}$ (Kellermann et al. 1989), respectively. The last column lists the luminosity in Watts Hz$^{-1}$ at $5(1+z)$ GHz. The luminosities were calculated from the distance modulus corresponding to redshift $z$ (Peebles 1971)

\begin{equation}
    m - M = 5 \log z + K(2) + K(3)
\end{equation}

where $m$ and $M$ are the apparent and absolute magnitudes, respectively, $z$ denotes redshift,

\begin{equation}
    K(2) = 2.5 \log \left( \frac{1}{1+z} \right) \alpha,
\end{equation}

and

\begin{equation}
    K(3) = 42.38 - 5 \log h + 5 \log \left[ \frac{\sqrt{1+z}}{q^2 z \left( qz + (q-1)\sqrt{1+2qz-1} \right)} \right]
\end{equation}

where $h$ is a scaling factor for the Hubble constant defined by the relationship $H_0=100h\, \text{km sec}^{-1} \text{Mpc}^{-1}$, $q$ is the deceleration parameter, and $\alpha$ is the spectral index of the radio source. The currently accepted values of $H_0$ (75 km sec$^{-1}$ Mpc$^{-1}$) and $q$ ($q_0=0.5$, corresponding to a flat universe) were used. The $K(2)$ term, which accounts for the cosmological redshift, simplifies to the expression given above when it is expressed in
frequency units. Since the QSO cores have a flat spectrum, we assume \( \alpha = 0 \) and consequently, \( K(2) = 0 \). The \( K(3) \) term is a relativistic correction factor which compensates for the decrease in observed energy per unit time.

The apparent and absolute magnitudes in Eqn 3 were converted to fluxes, where the apparent flux was then defined as the flux measured (listed in column 5 of Table 1) and the absolute flux represents the flux that would be measured if the QSO were moved to a position ten parsecs (pc) from earth. Equation 3 is then rewritten as

\[
(4) \quad \frac{F_e}{F_m} = \left( \frac{3.99 \times 10^8}{q^2 q_z (q + 1)(q^2 + 1)} \right)^2
\]

where \( F_e \) is the flux which would be measured if the QSO were at a distance of ten parsecs, and \( F_m \) is the flux actually measured. \( F_e \) is then multiplied by \( 4\pi(10 \text{ pc})^2 \), and the units converted to Watts/Hz, to get the intrinsic luminosity of the QSO listed in column 6 of Table 1. When the flux is corrected for redshift, the rank order of QSOs based on radio luminosity changes slightly, but not significantly. These are still the ten QSOs with the highest radio core luminosity at 5 GHz in the BQS, and these QSOs are radio-loud as defined by Kellermann et al. (1994).

PG 1226+023, also known as 3C 273, was not monitored during this campaign. Since this is one of the first QSOs identified, it has been observed numerous times in other studies and is a well known variable (Angione 1971).

We assume the QSOs in our sample are radio-loud because we are looking down the axis of the jet. For QSOs with jets of velocity \( v \), the jet emission is boosted by relativistic time dilation according to the following equation:
where $\beta = \frac{v}{c}$, $\gamma = \frac{1}{\sqrt{1 - \beta^2}}$, and $S_o$ is the observed emission, $S_e$ is the energy emitted, and $\theta$ is the angle between the jet and our line of sight (Robson 1996). When $\theta$ is small, the radio emission is significantly boosted. If we are looking down the jet and variability is caused by a shock wave propagating through the jet, we expect to see more short- and long-term variability in our radio-luminous QSOs than in less radio luminous QSOs in the BQS or other samples.
CHAPTER 3

DATA COLLECTION

The Apparatus

All observations were made with the National Undergraduate Research Observatory (NURO) 31-inch telescope near Flagstaff, AZ. A charge coupled device (CCD) camera with a 512x512 pixel chip was used to obtain exposures of the QSO fields. The field of view of the camera was approximately 4'x4', giving a scale of 0.49" per pixel. The filter used in all observations was the red (R) filter, which has a bandpass with full-width half-maximum (FWHM) of 1540 Å and a peak at wavelength 6000 Å. The R filter was used because of the CCD's increased quantum efficiency (QE) at that wavelength. QE determines the sensitivity of the CCD to photons that are incident upon it, and is a measure of photon detection. Photon counts are lost due to the following: reflection loss at the surface of the sensor, loss by absorption in the gate electrodes, loss in the gate insulator, and loss of carriers via recombination in the silicon substrate (Janesick & Elliot 1992).

Observations

Table 2 lists all the dates (Universal Time) on which observations were made. The QSOs were observed by making a series of four minute exposures for approximately three to four hours a night, for at least two consecutive nights for each QSO. All QSOs
were then observed for shorter durations at least three months later to look for long-term variability. Along with images of the QSOs, bias and flat field frames were also taken.

Table 2. UT Dates of Observations

<table>
<thead>
<tr>
<th>QSO</th>
<th>Nights Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG 0003+158</td>
<td>7-9 October 1994</td>
</tr>
<tr>
<td></td>
<td>20 October 1995</td>
</tr>
<tr>
<td>PG 1103-006</td>
<td>26 March 1995</td>
</tr>
<tr>
<td></td>
<td>14-15 April 1996</td>
</tr>
<tr>
<td></td>
<td>2-3 March 1997</td>
</tr>
<tr>
<td></td>
<td>28 February 1998</td>
</tr>
<tr>
<td></td>
<td>1-2 March 1998</td>
</tr>
<tr>
<td>PG 1222+228</td>
<td>26 March 1995</td>
</tr>
<tr>
<td></td>
<td>14-15 April 1996</td>
</tr>
<tr>
<td></td>
<td>2-3 March 1997</td>
</tr>
<tr>
<td>PG 1226+023</td>
<td>N/A</td>
</tr>
<tr>
<td>PG 1241+176</td>
<td>25-26 March 1995</td>
</tr>
<tr>
<td></td>
<td>15 April 1996</td>
</tr>
<tr>
<td></td>
<td>2-3 March 1997</td>
</tr>
<tr>
<td></td>
<td>28 February 1998</td>
</tr>
<tr>
<td></td>
<td>1-2 March 1998</td>
</tr>
<tr>
<td>PG 1302-102</td>
<td>25-26 March 1995</td>
</tr>
<tr>
<td></td>
<td>15 April 1996</td>
</tr>
<tr>
<td></td>
<td>2-3 March 1997</td>
</tr>
<tr>
<td></td>
<td>28 February 1998</td>
</tr>
<tr>
<td></td>
<td>1-2 March 1998</td>
</tr>
<tr>
<td>PG 1538+477</td>
<td>14-15 April 1996</td>
</tr>
<tr>
<td></td>
<td>17 July 1996</td>
</tr>
<tr>
<td>PG 1718+481</td>
<td>14 June 1994</td>
</tr>
<tr>
<td></td>
<td>5-7 July 1994</td>
</tr>
<tr>
<td></td>
<td>7,9 October 1994</td>
</tr>
<tr>
<td></td>
<td>28 February 1998</td>
</tr>
<tr>
<td></td>
<td>1 March 1998</td>
</tr>
<tr>
<td>PG 2308+098</td>
<td>20-22 October 1995</td>
</tr>
<tr>
<td></td>
<td>17-18 July 1996</td>
</tr>
<tr>
<td>PG 2344+092</td>
<td>7-9 October 1994</td>
</tr>
<tr>
<td></td>
<td>20-22 October 1995</td>
</tr>
</tbody>
</table>

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A bias frame is an image of the two-dimensional, additive background that is applied to all images. A CCD collects charge, which is then transferred to an on-chip amplifier to be converted to an output voltage. During this process, however, charge may be lost. The charge transfer efficiency of a CCD increases when there is a substantial number of electrons located in the potential wells. Therefore, for images with small numbers of counts, the output voltage is more proportional to the actual number of photons striking the CCD when there is a bias (or pedestal) charge applied. The bias frame is a zero-second exposure. Since no photons reach the CCD during the bias frame, the counts are due only to the applied pedestal charge. When a pedestal charge is applied to the CCD, however, there may be a pattern of "hot" (high valued) pixels due to the fact that the electronics do not always apply a pedestal charge uniformly. Bias frames are used to map this pattern of hot pixels that would show up in every image. Since this pattern may vary slightly during the night, bias frames are taken both at the beginning and at the end of the night and then averaged during the reduction process.

Flat field frames measure the pixel-to-pixel variations in the CCD sensitivity. The pixels have varying QEs as a result of small structural variations on the CCD. The pixels have different sensitivities, and these differences are wavelength dependent. Therefore, we exposed the CCD, using the R filter, to the twilight sky which served as a uniform illumination. Any variation in the frame is directly related to varying QEs. Occasionally, however, the twilight sky would get dark enough for stars to appear in the flat frames. The telescope tracking was turned on during flat field exposures to ensure no star trails were in the frame to keep the affect of non-uniform illumination to a minimum. Between exposures, the telescope was moved a few arcseconds so that if a star did appear.
in the frame, it would not appear in the same place in each flat field frame. Flat field frames were then combined using a median filter in the data reduction process to create a map of the pixel variations.

Before starting a QSO exposure, check stars were confirmed to be included within the field of view. In order to determine whether a QSO was truly varying, the QSO brightness was monitored with respect to check stars in the same field. The check stars were averaged together to create a synthetic star. The differential magnitudes (magnitude difference between the QSOs and synthetic stars) were analyzed. Three to eight check stars, depending on availability, were used to guard against confusing QSO variability with stellar variability. This method is effective for dealing with changes in sky, background, and instrumental noise. Since the field of view was small, we assumed that the effects of seeing, thin clouds, or transparency were uniform across the image. Thus, when a plot is made of differential magnitudes versus time, any spikes or other changes should be intrinsic to the QSO and not a result of transparency changes or clouds. Figure 1 shows a typical QSO field with the QSO, PG 1103-006, and the four check stars in the field labeled.
Figure 1. Field showing PG 1103-006 and check stars
CHAPTER 4

DATA REDUCTIONS

CCD Reductions

All CCD reductions and photometry were done using the Image Reduction and Analysis Facility (IRAF) software package, which was written by the National Optical Astronomy Observatories (NOAO). The reductions were done in three steps: applying bias frames, applying flat field frames, and removing cosmic rays.

First, the structure in the bias charge that occurred in every image needed to be mapped out. The average pedestal charge for each image—bias frames, flat field frames, and QSO images—is determined by analyzing the overscan region. The overscan region is the last 40 columns of each image, which are not exposed to light. These 40 columns read beyond the physical dimensions of the CCD chip to characterize the pedestal charge. Each row in the overscan region is averaged, and then a first order polynomial function is fit to these average counts. This function defines the average pedestal charge that was calculated and applied to each image. Once the average pedestal charge was subtracted from each bias frame, the counts left over represent the structure in the bias charge. The bias frames, with pedestal charges subtracted, were averaged. This average was subtracted along with the pedestal charge from all images.

Next, the flat field frames were combined using a median filter in case stars or cosmic rays appeared in the field. This median flat field image is a map of the
pixel-to-pixel variations due not only to the electronics, but also to specks of dust in the optical path. The QSO images were then divided by the flat field map to remove these variations.

The final step in the CCD reduction process was to remove cosmic rays. Cosmic ray events are very hot pixels or even streaks within an image resulting from charged particles passing through the CCD. The IRAF task COSMICRAY was used to correct these pixels. Typically, a detection threshold value of 8 times the mean flux of the surrounding pixels was set. Candidate pixels are identified if their flux is above the threshold value. The mean flux of the surrounding pixels, omitting the second brightest pixel after the candidate in case it is also a cosmic ray event, is then computed. If the candidate pixel's flux is greater than 20 times this newly computed mean, it is replaced by the mean of the four neighbor pixels. Because cosmic rays sometimes struck more than one pixel, this process was repeated until no pixels above the threshold value were located near objects of interest.

**Photometry**

Once the CCD reductions were complete, the IRAF packages APPHOT and DAOPHOT were used to perform photometry.

The PHOT task was used for aperture photometry when the QSO and all check stars in the field were isolated; this was the case for all but three QSOs. IRAF has the ability to perform photometry for multiple apertures simultaneously, so a range of apertures of radius 6-24 pixels was used. PHOT determines the total number of counts, which includes the sky background and the object, that are contained within an aperture. A sky annulus centered on the star or QSO, with a width of 8 pixels and an inner radius
of 24 pixels was chosen. This sky annulus was chosen because it was close enough to the star or QSO to adequately represent the sky in that area of the image, but far enough away that negligible amounts of light from the check star or QSO were included. A sky fitting algorithm that computed the mode from the histogram of sky pixels in the annulus was used to calculate the sky background counts. Once a sky value is computed, it is subtracted from the total counts to yield the net counts from the object of interest. The instrumental magnitude is computed as follows:

\[ \text{mag} = \text{zmag} - 2.5 \times \log_{10} \left( \frac{\text{counts}}{\text{itime}} \right) \]

where \( \text{zmag} \), which was set to 26, is the zero point offset for the magnitude scale, and \( \text{itime} \) is the exposure time in seconds.

Once all available data for a single QSO was reduced, the next step was to choose an optimal aperture from the range of radii measured by PHOT. A large aperture was desired so that all of the light from an object was collected, but large apertures include a significant amount of noise from the background sky. A small aperture cuts down on the noise, but not as much object light is included and thus a fraction of the object light is measured. To determine the optimal aperture, a statistical analysis of the variance in the differential magnitudes was performed for PG 1538+477. The goal was to pick the largest aperture possible before the noise, as measured by the variance in differential magnitude, increased significantly. The Modified Levene Test (Neter et al. 1996), which tests for the constancy of variance, was used. This test was chosen because it is robust against serious departures from normality. Check star 1 was the brightest of the six check stars in the field. For each image, differential magnitudes were calculated by subtracting...
each check star's magnitude from check star 1. For each differential magnitude, the Modified Levene Test was first performed on data from all apertures. Since this included large apertures, the variances were not constant because the larger apertures contained more noise. Then one by one, apertures were excluded from the test to determine at what point the variances remained constant. The results from this analysis are shown in Table 3.

Table 3. Results from Analysis of Variance Using the Modified Levene Test

<table>
<thead>
<tr>
<th>Apertures</th>
<th>Star 1-Star 3</th>
<th>Star 1-Star 4</th>
<th>Star 1-Star 5</th>
<th>Star 1-Star 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 through 24</td>
<td>.000</td>
<td>.003</td>
<td>.000</td>
<td>.000</td>
</tr>
<tr>
<td>6 through 21</td>
<td>.002</td>
<td>.022</td>
<td>.003</td>
<td>.001</td>
</tr>
<tr>
<td>6 through 18</td>
<td>.205</td>
<td>.381</td>
<td>.191</td>
<td>.052</td>
</tr>
<tr>
<td>6 through 15</td>
<td>.496</td>
<td>.606</td>
<td>.542</td>
<td>.271</td>
</tr>
<tr>
<td>6 through 12</td>
<td>.559</td>
<td>.631</td>
<td>.717</td>
<td>.148</td>
</tr>
<tr>
<td>6 and 9</td>
<td>.487</td>
<td>.758</td>
<td>.701</td>
<td>.130</td>
</tr>
</tbody>
</table>

The first column indicates which apertures were included in the test. Apertures are expressed in pixel radii. The other four columns list which differential magnitudes the test was performed on, e.g., "Star 1-Star 3" means that the magnitude for check star 1 was subtracted from the magnitude for check star 3. The numbers listed in these four columns are observed significance values, or p-values.

The Modified Levene Test is a form of hypothesis testing. The null hypothesis, \( H_0 \), is the hypothesis that is accepted unless the data shows otherwise. If the data proves the null hypothesis does not hold, then an alternative hypothesis, \( H_A \), is accepted. For the Modified Levene Test, the \( H_0 \) is all variances in question are equal, and the \( H_A \) is at least
one of the sample variances is different. When the test is performed, a p-value is determined. The p-value is a measure of the risk in rejecting $H_0$ and accepting $H_A$ when $H_0$ is in fact true for the given data set. Therefore, a p-value that is smaller than the significance level being tested to is enough evidence to reject $H_0$ and accept $H_A$. For the purposes of the Modified Levene Test, a low p-value says that the variances are significantly different.

From the p-values in Table 3, apertures with radii of 18 pixels or less appear to have constant variance, meaning they are small enough that minimal amounts of background noise were included. Although the results for a radius of 18 pixels were statistically significant at the 99% confidence level, an aperture with radius of 15 pixels (14.7 arcseconds in diameter) was chosen because the p-values were more consistently large. Thus, differential magnitudes calculated from an aperture with radius of 15 pixels were used for statistical analysis. For QSO fields that required the DAOPHOT package for photometry, only one aperture may be specified. For these QSOs, the same aperture with radius of 15 pixels was used.

DAOPHOT was used for three QSO fields: PG 1103-006, PG 1241+176, and PG 2308+098. For PG 1103-006, the QSO itself had a star nearby. The IMEXAMINE task in IRAF was used to produce a radial profile plot centered on the QSO, and showed that the neighbor star fell within the sky annulus. Figure 2 is a radial profile plot for PG 1103-006; it is centered on the QSO and shows the nearby check star within the sky annulus, which is marked with dashed lines.
Figure 2. Radial profile plot of PG 1103-006 showing how light from the nearby star falls within the sky annulus (dashed lines).

Since the increased counts due to the neighbor would result in an inaccurate sky background value, DAOPHOT was used. PG 1241+176 also had a neighbor star close to the QSO. A radial profile plot showed the light from the neighbor fell within the sky annulus for the QSO. PG 2308+098 had two bright check stars with close companions, and a radial profile plot showed that for both bright check stars, their neighbors were located within the sky annulus.

DAOPHOT was developed by Peter Stetson of the Dominion Astrophysical Observatory to deal with crowded-field stellar photometry. DAOPHOT models the point
spread function (PSF) for each image, fits the model PSF to each star in the image, and then determines magnitudes for each star. The PSF is the two-dimensional brightness distribution produced in the detector by the image of a point source (Stetson 1987).

Due to changes in seeing and guiding inaccuracies, a PSF model must be constructed for each image. DAOPHOT builds a PSF model by utilizing the best aspects of both analytical and empirical methods. The user has a choice of analytic functions to fit to the observed data; the penny1 function was chosen because it best approximated the sample data. This function is a two component model consisting of an elliptical gaussian core with lorentzian wings, where the gaussian core may be tilted but the lorentzian wings are elongated along the x- or y-axes. The penny1 function was well suited to our data, where tracking inaccuracies often produced elliptical PSFs. To provide a first-order approximation to the actual stellar profile, the penny1 function is fit to relatively bright stars (referred to as "PSF stars") using least-squares analysis and weighted by the signal-to-noise (SNR) of each star. The PSF model is constructed for the brightest PSF star first. For each subsequent star, the current PSF is shifted to its centroid and then scaled to match the observed light distribution. The residuals from the best fit are stored in an array. These residuals are scaled to match the intensity of the brightest PSF star, and then subsampled in the x and y directions. These subsampled residuals are weighted according to the SNR of each PSF star and then combined into a look-up table of profile corrections. The PSF task in IRAF is used to construct the model PSF, which is the sum of the analytic function and the look-up table of corrections. This task performs the least-squares analysis on pixels within one fitting radius of the centroid of a star. The fitting radius is defined by the parameter FITRAD. For each image,
IMEXAMINE was used to determine the FWHM of at least two bright stars; the FWHMs were then averaged and rounded to the nearest integer value. FITRAD was defined as this integer value.

Once a PSF model is obtained, it is then checked for accuracy and, if needed, refined. The IRAF task NSTAR applies the PSF model to the PSF stars and their close neighbors. A starting estimate of the centroids and their instrumental magnitudes is required as input for NSTAR; these estimates were provided by the APPHOT task as outlined previously. PG 1103-006 and PG 1241+176 had bright, isolated stars that produced a good PSF model. For these QSOs, the next step was to use the task SUBSTAR to subtract the PSF stars from the image. The region that was subtracted from the image was from the centroid of the star out to a radius defined by the parameter PSFRAD. This was the radius of the stellar profile of the brightest star in the image, and was found from the radial profile plot. The point where the profile disappeared into the sky background was taken as the radius. The parameter PSFRAD was found for the first image from a single night of observations and used for subsequent images until SUBSTAR did not subtract the stars cleanly from the image; at this point PSFRAD was re-evaluated. For PG 2308+098, additional steps were needed because the brightest stars in the image had close neighbors. When NSTAR was run on images of this QSO, PSFRAD had to be changed so that it did not overlap with the fitting radius of a neighbor star. The separation between neighbor stars was defined as the distance between their centers. PSFRAD was then redefined as the difference between this separation and FITRAD. Once NSTAR applied the model to the PSF stars and their neighbors, SUBSTAR was used to subtract the neighbors from the image. The PSF task was run.
again on the subtracted image to build a second, improved PSF model since the two bright stars were now isolated. Figures 3 and 4 are surface plots of the brightest star in the field of PG 1103-006 and the PSF model for the same image, respectively.

After a PSF model was built and checked for accuracy, the final step was to use the task ALLSTAR to apply the model to all the check stars and QSO in the image. Great care was taken to ensure that the sky annulus started at a point at least ten pixels from the edge of PSFRAD so that it was outside the regions which were fitted to the PSF model. The PSF model is assigned a magnitude PSFMAG, which is the magnitude of the brightest PSF star as estimated using APPHOT. For each star in the image, ALLSTAR scales the PSF model to match the observed light distribution. By knowing the height of the PSF model and the height of the scaled model for the star, ALLSTAR can then calculate a corresponding magnitude for the star.

**Figure 3.** Surface plot of brightest star in field of PG 1103-006

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Data Organization

Once the photometry was complete, a script file was used to extract the variables of interest from the APPHOT and DAOPHOT output files. The variables of interest were the image name, object identification number, aperture radius, magnitude, and the x- and y-center. The image name not only contained the QSO name but also the observation number. The identification number was assigned by IRAF according to the order in which the photometry was performed and defined which object in the image the information pertained to. The photometry was usually done in the same order for every image so that each object would always have the same identification number. The aperture radius was important early in the research before an optimal aperture was chosen and used throughout. The x- and y-centers were important because they provided a check...
of the identification of the object. Once the variables of interest were collected, they were run through a program written in Visual dBASE not only to add the date for each observation, but also to put the data in a form more suitable for analysis. Also in dBASE, programs were written to check the identification numbers and modify the data if necessary. In some frames the identification number was assigned to the wrong object because either the photometry was done in a different order by individual collaborators, or a star was outside the field of view of the CCD and therefore could not be included in the photometry. Programs were written in dBASE to check for these events and then compensate for them. When this verification process was complete the data was exported to SPSS for statistical analysis.
Synthetic Star

Instead of comparing the QSO to each individual check star in the field, the check stars were combined into a single average "synthetic star" and then compared to the QSO (Choi & Herbst 1996). If a check star was missing from the frame, it had to be compensated for before the average was calculated. The check stars were analyzed before they were included in the average to ensure they were not varying significantly. Even if the check stars varied slightly, averaging them should minimize the impact of any fluctuations.

In order to create the synthetic star, the magnitude of each check star had to be converted to total counts according to

\[
\text{total counts} = \text{anti log}_{10} \left( \frac{\text{mag} - \text{zmag} - 2.5 \log(\text{itime})}{-2.5} \right)
\]

where itime is the exposure time in seconds. In some cases, a check star may have drifted out of the field of view and consequently was not included in the photometry. In these cases, the total counts for the missing check star were replaced with the average flux ratio between the missing check star and a different check star in the field multiplied by the total counts for the different check star. The flux ratio is equivalent to the
magnitude difference between the two check stars. For any individual image, the magnitudes may change but the differential magnitude for two stable check stars should remain the same. For example, let $\bar{C}_1$ be the average total counts for Check Star 1, the brightest check star in the field, across all images. Likewise, $\bar{C}_3$ is the average total counts for Check Star 3, a check star that has drifted out of the field in some images. Only the existing measurements were used to calculate $\bar{C}_3$. The flux ratio, $\bar{C}_3/\bar{C}_1$, was calculated. Finally, any missing values for Check Star 3 were replaced with $(\text{flux ratio}) \times C_1$, where $C_1$ is the total counts for Check Star 1 in that particular image. Once the missing values were compensated for, a synthetic star was created for each image from the total counts from all check stars. The total counts from the synthetic star were then converted back to a magnitude. The magnitude of the synthetic star was subtracted from the magnitude of the QSO. This magnitude difference now represents the differential magnitude between the QSO and the synthetic star. For each QSO, the differential magnitude was plotted for each image. Figures 5 through 13 show the differential magnitude plots for each of the nine QSOs observed in our sample. For each plot, the dates of the observations are denoted by different symbols. The horizontal axis represents the order of observations but it is not scaled to show the appropriate time between observing dates.

The average measurement error was 0.0078 magnitude, with a standard deviation of ±0.0028 magnitude.
Figure 5. Differential Magnitude Light Curve for PG 0003+158

Figure 6. Differential Magnitude Light Curve for PG 1103-006
Figure 7. Differential Magnitude Light Curve for PG 1222+228

Figure 8. Differential Magnitude Light Curve for PG 1241+176
Figure 9. Differential Magnitude Light Curve for PG 1302-102

Figure 10. Differential Magnitude Light Curve for PG 1538+477
Figure 11. Differential Magnitude Light Curve for PG 1718+481

Figure 12. Differential Magnitude Light Curve for PG 2308+098
Short Term Variability

Each QSO was analyzed for variability within a single night and between nights on a single observing run. An observing run is defined as a set of one or more consecutive nights of observations. To determine if variability within a single night occurred, linear regression was used. If the slope was significantly different from zero, the QSO was said to be variable during that night. If a QSO had consecutive nights with significant slope, more detailed analysis was performed to determine if the slopes were similar. The mean differential magnitudes for each night within an observing run were compared to one another to determine any significant difference. If the means were significantly different, the QSO was said to be variable. For two QSOs, the differential magnitude plots showed possible periodicity on two nights. For the best case,
PG 1241+176, a periodogram was created and analyzed to determine the frequency of any existing periodicity.

For each QSO, simple linear regression was performed for each night of data. Hypothesis testing was then run to determine how significant the slope was. For this test, the null hypothesis was that the slope was equal to zero; the alternative hypothesis was that the slope was either greater or less than zero. If the p-value was greater than the 95% significance level, the QSO was said to have varied within the course of the night. If a QSO had consecutive nights with significant slope, the data for both nights was grouped and linear regression was performed on the group using dummy variables. Any measurement \( Y_i \) may be expressed

\[
Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i
\]

where \( Y_i \) is the dependent variable (differential magnitude), \( \beta_0 \) is the y-intercept, \( \beta_1 \) is the slope, \( X_i \) is the independent variable (observation number), and \( \varepsilon_i \) is the random error for the measurement. If two nights are grouped into one set, the equation that represents any one measurement is now

\[
Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i1} X_{i2} + \varepsilon_i
\]

where \( X_{i1} \) refers to the observation number and \( X_{i2} \) is a dummy variable that refers to which night the data comes from. The dummy variable is set to 1 if the data comes from
the first night, or 0 if it comes from the second night. Therefore, rewriting Equation 9 for a measurement coming from the first night \((X_2 = 1)\) gives

\[
Y_i = (\beta_0 + \beta_2) + (\beta_1 + \beta_3)X_{i1} + \varepsilon_i
\]

where \(\beta_3\) is now an indication of how much greater or smaller the slope is for the first night. To see if the slope is significantly different, hypothesis testing is done where the null hypothesis is \(\beta_3 = 0\) and the alternative hypothesis is \(\beta_3 \neq 0\). If \(\beta_3 = 0\), then the slopes are the statistically the same. Thus, a p-value of less than 0.05 is enough evidence to reject the null hypothesis \((\beta_3 = 0)\) and accept the alternative hypothesis \((\beta_3 \neq 0)\), or the slopes are not statistically similar.

To determine if the mean differential magnitude varied significantly, an Analysis of Variance (ANOVA) was performed. An ANOVA by itself is not conclusive; the null hypothesis for an ANOVA is that all means are equal, and the alternative hypothesis is that at least one mean is significantly different. Therefore, additional testing is required to determine exactly which nights had significantly different means. The only way to accomplish this while keeping the significance level constant is by performing a multiple comparison test, such as Tukey's Honestly Significant Difference (HSD) test (Neter et al. 1996). The Tukey HSD test was performed at the 95% significance level. The null hypothesis for the Tukey HSD test is that the means are equal, and the alternative hypothesis is that the means are not equal. Therefore, a p-value of less than 0.05 is enough evidence to reject the null hypothesis and instead accept the alternative that the means are different.
Two QSOs, PG 1241+176 and 1302-102, appeared to show some periodicity in their differential magnitude plots for the nights of 25-26 March 1995 (see Figures 8 and 9). Since data from 25 March 1995 for PG 1241+176 showed the best signs for periodicity, in-depth analysis was performed only on this data set. A periodogram, which is the square of the discrete Fourier transform, was constructed in order to determine if any periodicity existed and, if so, at which frequency. The data was first detrended, which removes the base band peak of the periodogram. The base band peaks corresponds to the first-order slope of the data; any subsequent peaks correspond to the periodicity about that slope. Any peaks observed in the periodogram were analyzed to determine their significance. To do this, the peak was compared to the expected value due to random measurement errors. For each image of PG 1241+176, the flux ratio between the brightest and dimmest star in the field was calculated. This was done because the magnitude for this QSO was similar to that for the dimmest check star. Linear regression was then performed on each night separately. The standard deviation about the regression line was found, and then all standard deviations were averaged (weighted by sample size). This value represents the expected variation. The expected fractional variation for 25 March 1995 was found by dividing the average standard deviation by the average flux ratio for that night. By knowing the expected fractional variation for the night of 25 March 1995 and the average flux ratio between the QSO and the synthetic star for the same night, the expected variation for that night can be calculated. Since the periodogram is the Fourier transform squared, its peak is the square of the amplitude of variation. If the square root of the peak value of the periodogram is at least three times
greater than the expected variation, the peak is significant and corresponds to the
frequency of a real periodic variation.

PG 1226+023 (3C 273) was analyzed by conducting a literature search to study
the results of others.

**Long Term Variability**

To determine if a QSO had long-term variability, the mean differential
magnitudes for each night from one observing run were compared to those from nights on
other observing runs using the Tukey HSD. If the means were significantly different
between observing runs, the QSO was said to be a long-term variable.

Again, PG 1226+023 (3C 273) was analyzed by conducting a literature search.
CHAPTER 6

RESULTS

PG 0003+158

This QSO showed a significant slope on the night of 8 October 1994 with a p-value of 0.002. The first observation of the evening was omitted from the analysis since it inexplicably fell 4.58σ below the mean. The slope for the night of 8 October was $-0.005 \text{ mag/hr}$, which is the rate at which the QSO increased in brightness that night. The slopes for the nights of 7 and 9 October 1994 were not significant. The mean differential magnitudes for the three nights of the 1994 observing run were not significantly different (p-values > 0.356)

The night of 20 October 1995 shows a significantly fainter brightness than the 1994 observations; the p-value for the Tukey HSD was 0.000. Figure 14 shows the error bar plot for PG 0003+158. The vertical axis is the same as on the differential magnitude plots—it represents the (QSO - Synthetic Star) differential magnitude. The squares symbolize the mean differential magnitude for the night listed on the horizontal axis and the bars represent the 95% confidence interval about the mean according to

\[
\bar{x} \pm \left( z \frac{\sigma}{\sqrt{N}} \right)
\]

(11)
where $\bar{x}$ is the mean differential magnitude, $z$ is the $z$-value corresponding to a total area equal to 0.05 in the tails of the standard normal distribution, $\sigma$ is the observed standard deviation of each night, and $N$ is the sample size of each night. Directly above each date on the horizontal axis is the sample size $N$, or the number of images taken that night.

**Figure 14.** Error bar plot for PG 0003+158

Di Clemente et al. (1996) observed PG 0003+158 three times between July 1995 and Dec 1992, and found its brightness did not vary by more than 0.7 times the average measurement noise, or $0.7\sigma$ ($\sigma \leq 0.038$ magnitude). Since we are testing at the 95% confidence level (which corresponds to $1.96\sigma$), the observations by Di Clemente et al. (1996) do not meet our criterion for significant variations.

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The only night that shows a statistically significant slope is 2 March 1998 (p-value = 0.006). Since only three images were taken on that night, however, we do not believe the evidence is strong enough to support this conclusion.

The 1996 observations are significantly brighter than the 1997-1998 observations and the one image taken in 1995 (see Figure 15). Since only one image was taken in 1995, its brightness then is somewhat uncertain, although the differential magnitude for this night is similar to the differential magnitudes measured in 1997-1998.

![Figure 15. Error bar plot of PG 1103-006](image_url)

With one exception, all observing runs have significantly different mean differential magnitudes; the Tukey HSD p-values range from 0.000 to 0.036. The night of 2 March
1997, however, does not have a significantly different mean than the night of 1 March 1998 (p-value = 0.075, which is slightly above the 0.05 value regarded as significant). The night of 3 March 1997 has a significantly different mean differential magnitude than any night in the 1996 and 1998 observing runs (p-values ≤ 0.009). Short-term variation was also seen—the mean differential magnitude for 14 April 1996 is significantly brighter than the mean from 15 April 1996 (p-value = 0.000). Since the number of images taken on these two nights was large, the confidence intervals about the means were small as a result; this fact contributed to the means being found significantly different.

**PG 1222+228**

No nights had a significant slope for this QSO. Figure 16 shows the error bar plot for PG 1222+228.

Only one image was taken on 25 March 1995, but it appears to be within the range of magnitudes for all other nights. The mean differential magnitudes for the 1996 observing run are significantly fainter than the means from the 1997 run (p-values = 0.000).
Figure 16. Error bar plot for PG 1222+228

PG 1226+023

This QSO, otherwise known as 3C 273, was not observed during this campaign. All results are drawn from a literature search.

"Flashes" of brightness with times scales of a day have been observed as far back as 1965 (Angione 1971). More recently, 3C 273 experienced substantial outbursts in 1983 and 1988 (Hooimeyer et al. 1992). Furthermore, flares were observed at all wavelengths in 1990 and 1991 (Robson et al. 1993). The 1988 flares produced optical variations of several percent per day, with the amplitude of repeated flares 30-40% (Courvoisier et al. 1988). However, short term variability does not always occur—it was
not seen by Angione in 1968, nor by Lawrence, Ostriker, and Hesser in 1967 (Angione 1971).

3C 273 has been described as having near constant flux densities with intervals of violent activity (Roland, Teyssier & Roos 1994). Angione (1973) studied the Harvard historical plate collection and found that 3C 273's mean brightness remained essentially constant during the 60 to 70 years of photometric coverage, although it did show systematic trends with time scales on the order of 10 to 20 years. Lloyd (1984) also reported 3C 273 varied by approximately 1.3 magnitudes on a nine year time scale. Bozyan, Hemenway & Argue (1990) report a Δm_B (i.e., range between brightest and faintest magnitudes in the B band measured during observation period) of 0.87 between 1974 and 1987, and 0.79 in 1984.

PG 1241+176

No nights had a significant slope, but the differential magnitudes appeared to show signs of periodicity on the nights of 25 and 26 March 1995 (refer to Figure 8). To determine if periodicity did exist, the night of 25 March 1995 was studied in detail since it showed the most promise.

The periodogram for the night of 25 March 1995 (detrended data) is shown in Figure 17. The peak at approximately 2 x 10^{-4} Hz corresponds to a period of 1.4 hours. To determine if this peak was significant, we first determined the expected fractional variation. We assumed that since the synthetic star was an average of all the check stars in the field, the synthetic star was dominated by the brightest check star. Furthermore, the QSO was similar in magnitude to the dimmest check star. The average variation in flux ratio between the brightest and dimmest check stars in the field, across all nights,
was 0.28. The average flux ratio for these two stars on the night of 25 March 1995 was 40.4. Therefore, on the night of 25 March 1995 the expected fractional variation was 0.0068. The average flux ratio between the QSO and the synthetic star for the night of 25 March 1995 was 10.53; the expected variation for the QSO and the synthetic star flux ratio is the product of the average flux ratio and the expected fractional variation, or 0.072. The vertical axis of a Fourier transform gives the amplitude of the variation in units of flux ratio (equivalent to differential magnitude); since the periodogram is the square of the Fourier transform, the square root of the peak (flux ratio)^2 value in Figure 17 represents the variation at the frequency of the peak.

Figure 17. Periodogram for PG 1241+176 on the night of 25 March 1995
The square root of the peak (flux ratio)² value in Figure 17 is 0.1518. This observed variation is only 2.2 times greater than the expected variation of 0.072 (i.e., 2.2σ), which is not considered a significant variation. Since the night of 25 March 1995 for PG 1241+176 appeared to be the best case for periodicity and failed to prove significant, in-depth analysis for periodicity on other nights or for other QSOs was deemed unnecessary.

Figure 18 displays the error bar plot for PG 1241+176. For the nights of 25 and 26 March 1995, the QSO had the same differential magnitude (p-value = 0.066).
Due to the small sample size on the night of 15 April 1996, the mean differential magnitude for this night could not be distinguished from the mean from 25 March 1995 (p-value = 0.123), but it was significantly greater (i.e., the QSO was dimmer) than the night of 26 March 1995 (p-value = 0.002). The 1997 and 1998 observing runs statistically have the same mean differential magnitudes (p-value ≥ 0.066); the QSO appears to have dimmed between the 1996 and 1997 observing runs (p-value = 0.000).

PG 1241+176 has also been observed by Jang & Miller (1995) on 26 May, 30 May, and 8 June 1994. On these nights, they measured 3.2σ, 3.9σ, and 5.5σ variability, respectively, within a time scale of approximately 3 hours (σ ≤ 0.011 magnitude). Jang & Miller's findings support earlier results by Carini (1990) which showed short period variability.

PG 1302-102

The nights of 2 March and 3 March 1997 both had significant slopes when linear regression was applied to the differential magnitude plot. On the first night, the slope was −0.033 mag/hr with a p-value of 0.000. The second night, 3 March 1997, had a slope of −0.014 mag/hr and a p-value of 0.018. Since consecutive nights had a significant slope, hypothesis testing was done to determine if the slopes were similar for the two nights. The resulting p-value was 0.048, so the null hypothesis (β3 = 0, or equal slopes) was rejected and the alternative hypothesis (β3 ≠ 0, or different slopes) was accepted. Figure 19 shows the error bar plot for PG 1302-102. The mean for the four observations on 15 April 1996 cannot be statistically distinguished from the mean differential magnitudes from the three nights of the 1998 observing run (p-value ≥ 0.190). Between
each of the four observing runs, however, the mean differential magnitudes varied significantly (p-values = 0.000).

Bozyan, Hemenway & Argue (1990) report that PG 1302-102 shows long-term variability; this QSO has been observed to vary by more than one magnitude based on observations separated by more than three years.

![Error bar plot for PG 1302-102](image)

**Figure 19.** Error bar plot for PG 1302-102

**PG 1538+477**

None of the three nights this QSO was observed have a significant slope. The observations on 14 April 1996 have a significantly higher mean differential magnitude (i.e., the QSO was dimmer) than the night of 17 July 1996 (p-value = 0.003). The mean differential magnitude for the night of 15 April 1996 cannot be statistically distinguished
from the means of the other two nights the QSO was observed. Figure 20 shows the error bar plot for PG 1538+477.

![Figure 20. Error bar plot for PG 1538+477](image)

Di Clemente et al. (1996) observed PG 1538+477 for three nights within eight months and report detecting long-term variability. During their second and third nights of observations, the QSO mean differential magnitudes were $2.5\sigma$ and $6.1\sigma$ ($\sigma \leq 0.067$ magnitude) below the mean differential magnitude recorded for the first night.

**PG 1718+481**

The nights of 14 June 1994, 5 and 6 July 1994 had significant slopes (0.003, 0.001, and $-0.001$ mag/hr, respectively) on the plot of differential magnitude (p-values were 0.000, 0.005, and 0.013 respectively). The nights of 5 and 6 July 1994 were
analyzed since they were consecutive nights with a significant slope; in-depth testing showed the slopes were not equal (p-value = 0.0071). Figure 21 shows the error bar plot for PG 1718+481.

Figure 21. Error bar plot for PG 1718+481

As can be seen in Figure 21, the 95% confidence intervals vary greatly, and statistically distinguishing between mean differential magnitudes was complicated. Table 4 shows the results of the Tukey HSD test; an "X" in a square symbolizes a significant (at the 95% confidence level) difference in the means for the two nights being compared. The 1998 observing run has a significantly lower mean differential magnitude (i.e., the QSO brightened) than any of the 1994 observations (p-values ≤ 0.045). During the July 1994 observing run, the QSO appeared significantly dimmer on 5 July.
PG 1718+481 has been observed by Di Clemente et al. (1996) to vary by 2.3σ over the course of 13 months (σ ≤ 0.033 magnitude). Also, short-term variability has been observed by Jang & Miller (1995) during two nights in Aug 94; the QSO varied by 2.6σ over the course of 3.3 hours one night, and by the same amount in 3.8 hours on the other night (σ ≤ 0.011 magnitude).

Table 4. Results of the Tukey HSD for PG 1718+481

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</table>

PG 2308+098

The QSO has a significant slope of −0.01 mag/hr on the night of 22 October 1995 (p-value = 0.002).

Each night of the October 1995 observing had a significantly different mean differential magnitude (p-values = 0.000). The mean differential magnitude was also significantly higher (i.e., the QSO was dimmer) during the 1995 observing run than the
two nights it was observed in July 1996. The mean differential magnitude was not statistically different between the two nights observed in July 96. Figure 22 shows the error bar plot for PG 2308+098.

![Error bar plot for PG 2308+098](image)

Figure 22. Error bar plot for PG 2308+098

Di Clemente et al. (1996) did not observe any significant long-term variability in this QSO over the course of two months; PG 2308+098 varied by only 1.93σ (σ ≤ 0.063 magnitude).

**PG 2344+092**

The night of 22 October 1995 has a significant slope of 0.005 mag/hr (p-value = 0.041). Additionally, the night of 22 October 1995 has a significantly lower mean differential magnitude (i.e., the QSO was brighter) than the other two nights during this observing run (p-value = 0.000).
The mean differential magnitudes for the 1994 observing run are significantly lower (i.e., the QSO was brighter) than the means during the 1995 observing run. Figure 23 shows the error bar plot for PG 2344+092.

Short-term variability has been detected by Jang & Miller (1997) during two nights in November 1994. On 23 November 1994, PG 2344+092 had 3.3σ variation over the course of 3.8 hours. The next night, 24 November 1994, the QSO varied by 7.2σ in 3.9 hours. Additionally, on 24 November 1994 the QSO showed a steep decline in brightness of approximately 0.16 magnitudes in 3.7 hours (σ ≤ 0.011).

Long-term variability, however, was not detected when this QSO was observed by Di Clemente et al. (1996) over the course of five months. Lloyd (1984) describes PG 2344+092 as a well-observed flat-spectrum radio source that shows only modest
variations over periods of approximately 80 years. Additionally, Angione (1973) reported that the mean brightness of this QSO has remained essentially constant during the 60 to 70 years of photometric coverage.
CHAPTER 7

CONCLUSIONS

Table 5 lists the results of this monitoring program. Short-term variability is defined as variability occurring within a single night or between nights of a single observing run. Long-term variability is defined as variability occurring between observing runs. With one exception (June and July 1994 observing runs for PG 1718 + 481), observing runs were separated by at least three months.

Table 5. Results of monitoring program

<table>
<thead>
<tr>
<th>QSO</th>
<th>Short-term Variable</th>
<th>Long-term Variable</th>
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<tr>
<td>PG 0003+158</td>
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<tr>
<td>PG 1103-006</td>
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<td>Yes</td>
</tr>
<tr>
<td>PG 1222+228</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>PG 1226+023</td>
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<td>Yes</td>
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<tr>
<td>PG 1241+176</td>
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<td>Yes</td>
</tr>
<tr>
<td>PG 1302-102</td>
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<td>Yes</td>
</tr>
<tr>
<td>PG 1538+477</td>
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<td>Yes</td>
</tr>
<tr>
<td>PG 1718+481</td>
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<tr>
<td>PG 2308+098</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>PG 2344+092</td>
<td>Yes</td>
<td>Yes</td>
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</tbody>
</table>

We find seven out of ten QSOs exhibit short-term variability. PG 1222+228, PG 1538+477, and PG 1718+481 did not display any short-term variation. All ten of the QSOs displayed some type of long-term variability.

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To determine the significance of our results, we compared our findings to those from monitoring programs looking for optical variability in both radio-loud and radio-quiet QSOs.

Jang & Miller (1997) looked at samples of both radio-loud and radio-quiet QSOs for short-term variability. They defined radio-loud as those QSOs having \( R > 1 \) as defined by Kellermann et al. (1989). Two out of ten radio-quiet QSOs showed evidence for variability (compared to seven of ten of our radio-loud QSOs that showed short-term variability). For their radio-loud QSOs, six out of seven QSOs showed short-term variability. PG 2344+092 was also included in the Jang & Miller sample and showed signs of short-term variability.

Smith & Nair (1995) looked at the times scales of long-term quasi-sinusoidal fluctuations in QSO light curves, where "time scale" was defined as the time in years required for a complete cycle of brightening and fading (excluding flares). Out of the 18 radio-quiet QSOs in their sample, 7 showed credible evidence of base-level oscillations exceeding the observational scatter (compared to all ten of the radio-loud QSOs in our sample that showed long-term variability). For the "classical" radio-loud QSOs in the study, 42 out of 60 showed signs of long-term variability. PG 0003+158, PG 1226+026, and PG 2344+092 were included in the Smith & Nair study. The "classical" radio-loud QSOs in the Smith & Nair sample were initially detected due to their radio emission, and are therefore assumed to be radio-loud as defined by Kellermann et al. (1989).

We assume our QSO cores have high radio luminosities because they have a jet of relativistic material aligned close to our line-of-sight. If this is the case we would expect to see more variability than in a sample of radio-quiet QSOs if the shock in the jet is the...
cause of variability. Based on the results stated above, there is evidence that our radio-
loud QSOs are more likely to have short-term variations compared to samples of radio-
quiet QSOs. This finding supports the model of QSO variability being caused by shocks
in the relativistic plasma jet.
REFERENCES


Carini, M.T. 1990, Ph.D. thesis, Georgia State University


Neter, J., Kutner, M.H., Nachtsheim, C.J., & Wasserman, W., 1996, Applied Linear Regression Models (Irwin)


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