AN EVENT IN THE LIGHT CURVE OF 0957+561A AND PREDICTION OF THE 1996 IMAGE B LIGHT CURVE

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ABSTRACT

CCD photometry of the gravitational lens system 0957+561A, B in the g and r bands was obtained on alternate nights, weather permitting, from 1994 December through 1995 May using the Double Imaging Spectrograph (DIS) on the Apache Point Observatory (APO) 3.5 m telescope. The remote observing and fast instrument change capabilities of this facility allowed accumulation of light curves sampled frequently and consistently. The Honeycutt ensemble photometry algorithm was applied to the data set and yielded typical relative photometric errors of approximately 0.01 mag. Image A exhibited a sharp drop of about 0.1 mag in late 1994 December; no other strong features were recorded in either image. This event displays none of the expected generic features of a microlensing-induced flux variation and is likely to be intrinsic to the quasar; if so, it should also be seen in the B image with the lensing differential time delay. We give the expected 1996 image B light curves based on two values of the time delay and brightness ratio which have been proposed and debated in the literature. Continued monitoring of the system in the first half of 1996 should easily detect the image B event and thus resolve the time-delay controversy.

Subject headings: distance scale — gravitational lensing — quasars: individual (0957+561)

1. INTRODUCTION

The double quasar 0957+561A, B was the first gravitational lens to be discovered (Walsh, Carswell, & Weymann 1979). Its redshift is $z_0 = 1.41$, the separation of the two images is 6.1" and the lensing galaxy is at the center of a $z_L = 0.36$ cluster of galaxies. Shortly after the discovery, changes in brightness of the two quasar images were detected and measured by several groups (Lloyd 1981; Miller, Antonucci, & Keel 1981; Keel 1982; Schild & Weekes 1984; Schild & Cholfin 1986). The groups (Lloyd 1981; Miller, Antonucci, & Keel 1981; Keel 1982; Schild & Weekes 1984; Schild & Cholfin 1986). The double quasar 0957+561A, B was also the first system for which an attempt to measure the time delay was reported (Dyer & Roeder 1980; Florentin-Nielsen 1984). Since the differential time delay is inversely proportional to the Hubble parameter $H_0$ (Refsdal 1964), it can be in principle used to determine $H_0$. For the system 0957+561 with its many observational constraints (separation of images, intensity ratios, radio structure on VLA scale, VLBI jets, X-ray properties) a variety of lens models exist (Young et al. 1981; Narasimha, Subramanian, & Chitre 1984; Falco, Gorenstein, & Shapiro 1991; Kochanek 1991).

There is, however, a degeneracy between smoothly distributed matter of the underlying galaxy cluster and the matter in the lensing galaxy itself (Gorenstein, Falco, & Shapiro 1988). Further uncertainty in the determination of $H_0$ in the double quasar arises as a result of a controversy in the measured value of the time delay between different groups, ranging between 1.1 and 1.5 yr (Borgeest &Refsdal 1984; Falco, Gorenstein, & Shapiro 1985, 1991; Vanderriest et al. 1989; Schild 1990; Kochanek 1991; Rhee 1991; Lehár et al. 1992; Press, Rybicki, & Hewitt 1992b; Schild & Thomson 1995; Pelt et al. 1994, 1995). Prompted by this disagreement, we decided to include 0957+561 in our lens monitoring program.

2. DATA ACQUISITION AND REDUCTION

Images were obtained at the Apache Point Observatory (APO)2 3.5 m telescope with the Double Imaging Spectrograph (DIS) in the imaging mode. The DIS has two independent collimators and cameras for the blue and red sides. The incoming light is split by a dichroic with a transition wavelength of 5350 Å. On the blue side the detector is a thinned, UV-coated SITe (formerly Tektronix) 512 × 512 CCD, and on the red side it is a thinned 800 × 800 TI chip. The measured scales are 1.086 pixel−1 in the blue and 0.610 pixel−1 in the red (Lupton 1995). Gunn-Than g and r filters were used on the blue and red sides for the lens monitoring program. Since the filter wheel blocks part of the field, the effective area on the red chip was reduced to $384' \times 256'$ and on the blue chip to $396' \times 266'$. The gain and linearity of the chips were recently measured by Gloria (1995). On the blue side the gain is 1.00 electron ADU−1; on the red side it is 1.83 electrons ADU−1. The blue chip is linear to 61,000 ADU, and the red chip is linear to 48,000 ADU. These figures were used to exclude overexposed stars on the g and r frames, respectively.

The double quasar (among other lenses) has been monitored continuously between 1994 December and 1995 May; weather and equipment permitting, we obtained two to four images of 0957+561 in g and r bands every other night. All data were acquired remotely from an observing station in

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2 APO is privately owned and operated by the Astrophysical Research Consortium (ARC), consisting of the University of Chicago, the Institute for Advanced Study, Johns Hopkins University, New Mexico State University, Princeton University, the University of Washington, and Washington State University.
Princeton. Several images with different exposure times were taken to encompass comparison stars with a wide magnitude range. The telescope was offset by 10°–20° between exposures to minimize spurious variations from bad pixels and to allow construction of sky flats from a median of program exposures. Images were taken mostly in nonphotometric conditions with typical seeing FWHM between 1.3 and 1.8. Roughly 20–45 minutes were devoted to lens monitoring on alternate nights, of which perhaps one-third were used to obtain the 0957+561 data; if not already in use, DIS was mounted on the telescope just for these observations.

CCD images were processed using IRAF’s CCDRED package. A “superbias” was created from a median of all bias images taken throughout the season and subtracted from each program exposure. The remaining variations in the mean bias level were subtracted by fitting a low-order spline to the overscan columns. Pixel-to-pixel sensitivity variations were removed using a sky flat field obtained by finding the median of 2 weeks of monitoring data. Images were grouped according to the Moon phase, with boundaries at first and third quarters. At least 14 exposures were combined for each sky flat.

After the preliminary data processing, aperture photometry was performed on the two quasar images and nine comparison stars. The aperture radius was limited to 3″ by the separation of the quasar images. A modal value of the sky from an annulus around each object was subtracted from the aperture flux. Objects with the peak flux exceeding the linearity threshold were flagged at this stage, as well as those with signal-to-noise ratio below 50. Images with three or more comparison stars were retained for differential photometry, resulting in 183 good $r$ exposures and 167 good $g$ exposures.

Light curves for the two quasar images in $g$ and $r$ bands were derived using the inhomogeneous CCD ensemble photometry algorithm developed by Honeycutt (1992). Following his notation, we briefly describe the least-squares solution method for measuring instrumental magnitudes of stars in a set of $ee$ exposures. The instrumental magnitude of star $s$ on exposure $e$ is given by

$$m(e, s) = m_0(s) + em(e),$$

where $m_0(s)$ is the mean instrumental magnitude of star $s$ and $em(e)$ is the exposure magnitude for exposure $e$, representing exposure-to-exposure variations common to all stars due to exposure time, atmospheric extinction, etc. The quantity to be minimized is then

$$β = \sum_{e=1}^{ee} \sum_{s=1}^{s} [m(e, s) - m_0(s) - em(e)]^2 w(e, s),$$

where $w(e, s)$ is the weight given to instrumental flux of star $s$ in exposure $e$. This weight is set to zero if star $s$ is overexposed or missing. Otherwise, each well-exposed star is initially given the same weight $w(e, s) = 1$, which is later refined based on exposure-to-exposure variance of the instrumental flux of star $s$ ($σ[m_0(s)]$), and star-to-star variance of the instrumental magnitude offset in exposure $e$ ($σ[em(e)]$). Note that quasar images A and B are not included in the least-squares sum $β$ because of their expected variation.

Quasar variances $σ[m_0(A)]$ and $σ[m_0(B)]$ were obtained by fitting a functional form (constant + exponential) to the $σ[m_0(s)]$ versus $m_0(s)$ relation of comparison stars, and evaluating the fit at the quasar mean magnitudes $m_0(A)$ and $m_0(B)$. An implicit assumption in this procedure is that the quasar fluxes are measured with the same precision as the comparison stars. This results in a somewhat optimistic error estimate, because photometry of the quasar images is complicated by their proximity (overlapping point-spread functions [PSFs]) and the seeing-dependent light contribution of the galaxy underlying image B. These sources of errors have been thoroughly discussed by Schild & Cholfin (1986), who conclude that each effect contributes no more than 1% error in seeing better than 2″.

Approximate zero magnitude offsets in the two bands were calculated by comparison of instrumental $g$ and $r$ magnitudes with the data on five stars in the 0957+561 field published in Table 1 of Schild & Cholfin (1986). The rms scatter in relative magnitudes between the two data sets was 0.010 mag in $r$ and 0.017 mag in $g$. Detailed tabulation of the photometry and related quantities is available on line; send electronic mail to len@astro.princeton.edu for access information.

3. RESULTING LIGHT CURVES AND PREDICTIONS

Light curves for the $g$ and $r$ images of the QSO 0957+561A, B are shown in Figure 1. These light curves are characterized by high temporal resolution (data taken every other night when clear) and good photometric precision (0.01 mag for bright comparison stars, 0.02 mag for faint comparison stars and quasar images). Observations from the same night were combined to a single point on the light curve using a weighted average of individual exposures.

The solid line in Figure 1 displays our fits for the $r$ and $g$ monitoring data, following closely the method of Press, Rybicki, & Hewitt (1992a). We have adopted power-law structure functions, as suggested by these authors, with indices of 0.37, 0.08, 0.25, and 0.11 for the green A and B and red A and B images, respectively. The values for image A roughly agree with Press et al. (1992a), who find 0.27 and 0.34 for images A and B in their much longer data sample, which contains many events in both images (unlike our image B).

In each band, there is a significant drop in brightness of image A, with no corresponding drop in image B. In $g$ the drop of about 0.13 mag should be recognizable if it repeats in image B. We thus predict in Figure 2 the future shape of the $g$ light curve in image B for two different time delays: 536 days, obtained by analysis of radio data (Lehár et al. 1992) and a combined optical-radio sample (Press et al. 1992b), and 415 days obtained by Vanderriest et al. (1989) and Schild & Thomson (1995). The latter time delay is also advocated by Pelt et al. (1994, 1995).

Note also the offset in the ordinate for the two curves in Figure 2. Just as different methods of analysis yield different time delays $τ$, they also yield different magnitude offsets between $A(t)$ and $B(t - τ)$. Magnitude offset between images A and B could be in principle predicted from a lensing model of the system, but in practice it is frequently left as a free parameter. Thus, a reliable measurement of the image flux ratio would provide an additional constraint on the existing models. Press et al. (1992b) suggest an offset of 0.0950 mag for
the optical data, while Vanderriest et al. (1989) suggest one of 0.03 mag. We have tacitly assumed that the image flux ratios are constant from one optical band to another, neglecting reddening in the lensing galaxy and the light contribution of this galaxy to the measured instrumental fluxes.

Even after careful data reduction, light curves in Figure 1 show correlated variations in instrumental magnitudes of images A and B with an amplitude of 0.01–0.02 mag. A possible reason for such correlations is time variation of the residual large-scale structure in the sky flats used to remove pixel sensitivity variations across the field. Since quasar images are close to each other and preferentially located near the center of each frame, they will be flat-fielded differently from the comparison stars scattered across the frame. Another culprit might be seeing-induced variations in instrumental flux caused by overlapping PSFs of the two quasar images and the underlying galaxy. In any case, these systematic photometric errors are comparable to the statistical ones and small compared to the 1994 December image A event.

4. THE MICROLENSING HYPOTHESIS

There can be two causes for the observed variability of the quasar image: it can reflect an internal change in the luminosity of the quasar, or it can be a result of gravitational microlensing by compact objects along the line of sight to the quasar. Only intrinsic variability is expected to repeat in image B and can thus be used to measure the gravitational time delay. While it is possible that the feature is microlensing-induced, we argue that this scenario is unlikely because of its chromaticity and timescale.

The event amplitude in $g$ (0.13 mag) is significantly larger than in $r$ (0.08 mag), in contrast to the expected achromaticity of gravitational lensing. There is a possibility of measuring slightly different light curves in two bands if inner parts of the quasar accretion disk are “hotter” or “bluer” than the outer parts (Wambsganss & Paczynski 1991), but this second-order effect is not expected to produce differences as large as those observed.

The short duration of the event also disfavors the microlensing hypothesis. The typical microlensing timescale in the system 0957+561 for solar-mass stars is expected to be $\sim 30–100$ yr (Gott 1981; Young 1981). In order to explain a timescale of 2 weeks, one would have to invoke microlensing objects with masses $\sim 10^{-9} M_\odot$. This argument crucially depends on the assumption of low optical depth. If the optical depth to microlensing is of order unity, a microlensing event is usually caused by caustic crossing, and its duration is not directly related to the mass of the lensing object.

Clearly, the only secure way to resolve the dilemma is with observations of the image B light curve in 1996. In principle, this would still leave the possibility of accidental repeated microlens-induced features in the two images, but this is extremely unlikely in the case of the double quasar 0957+561 (Falco, Wambsganss, & Schneider 1991).

5. DISCUSSION

It has been widely appreciated (see, e.g., Blandford & Narayan 1992) that measurement of gravitational lens differential time delays may provide a simple (i.e., understood entirely from first principles), direct, and robust way of measuring absolute physical distances, and thus $H_0$, at large
redshifts. It is daunting that a decade and a half of observational work on gravitational lens systems has provided so little progress. The difficulties are, in a sense, subtle; the individual astronomical observations (image photometry) are reasonably straightforward, as is the theoretical interpretation of the resulting light curves.

One major problem is logistical. Obtaining small amounts of data (observing time) frequently and regularly with a large (nonsolar) telescope and using the same instrumentation is inconsistent with the operational modes of conventional nighttime observatories. Aside from its direct interest, we believe that the data set presented here demonstrates that remote observing and fast instrument change technologies now make such consistent synoptic projects practical.

In summary, we report a sharp event in the leading (A) image of the gravitational lens system 0957+561. The chromaticity, amplitude, and shape of this event argue for its intrinsic nature and against microlensing-induced variability. However, microlensing cannot be reliably excluded if the optical depth is close to unity. A detection of the observed feature in the light curve of the trailing (B) image in 1996 would confirm the quasar variability hypothesis and settle a long-standing controversy about the value of the gravitational time delay in the double quasar 0957+561.

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