THE OPTICAL GRAVITATIONAL LENSING EXPERIMENT MONITORING OF QSO 2237+0305

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ABSTRACT

We present results from 2 yr of monitoring of Huchra’s lens (QSO 2237+0305) with the 1.3 m Warsaw telescope on Las Campanas, Chile. Photometry in the $V$ band was done using a newly developed method for image subtraction. Reliable subtraction without Fourier division removes all complexities associated with the presence of a bright lensing galaxy. With the positions of the lensed images adopted from Hubble Space Telescope (HST) measurements, it is relatively easy to fit the variable part of the flux in this system, as opposed to modeling the underlying galaxy. For the first time, we observed smooth light variation over a period of a few months, which can be naturally attributed to microlensing. We also describe automated software capable of real-time analysis of the images of QSO 2237+0305. It is expected that starting from the next observing season in 1999, an alert system will be implemented for high-amplification events in this object. The time sampling and photometric accuracy achieved should be sufficient for early detection of caustic crossings.

Subject headings: galaxies: photometry — gravitational lensing — quasars: individual (Q2237+0305)

1. INTRODUCTION

The Optical Gravitational Lensing Experiment (OGLE) is a long-term project focusing on the detection and monitoring of microlensing events. During the second phase of the experiment, data are collected with the dedicated 1.3 m Warsaw telescope at the Las Campanas Observatory (LCO), Chile (Udalski, Kubiak, & Szymański 1997). Because of the intrinsically small probability of the microlensing phenomenon, the main targets are the densest stellar fields, namely, the Galactic Bulge and Magellanic Clouds (e.g., Paczyński 1996). Some telescope time, however, was also allocated to observations of other objects in which gravitational lensing is present, e.g., distant quasars lensed by foreground galaxies. Given good seeing at the Las Campanas Observatory and the amount of available telescope time, the OGLE II survey can provide good time coverage of the variability in a few selected multiply imaged lenses. Currently, two such systems are monitored by OGLE: QSO 2237+0305 and HE 1104−1805.

Objects of this kind are particularly interesting for cosmology in determining time delays. QSO 2237+0305 is a unique system and consists of a high-redshift quasar at $z=1.695$ quadruply lensed by a relatively nearby galaxy at $z=0.039$ (Huchra et al. 1985). Because light rays of the four images pass through the bulge of the foreground galaxy, the optical depth to lensing on individual stars could be as large as 0.4−0.9, depending on the image (Webster et al. 1991; Schneider et al. 1988), making microlensing very likely in Huchra’s lens. Moreover, the high degree of symmetry, short distance to the lensing galaxy, and small image separations produce predicted time delays of about 1 day or less (Schneider et al. 1988). Thus, intrinsic variability can be easily distinguished from microlensing effects. Microlensing has already been discovered in Huchra’s lens by Irwin et al. (1989) and confirmed later. Nevertheless, despite broad interest in this object, so far the best light curve consists of only 59 measurements in the $R$ band, spread over a period of about 8 yr, representing the combined efforts of many observers (Ostensen et al. 1996; Corrigan et al. 1991).

The traditional approach to photometry of this object, i.e., by modeling the underlying galaxy light or iterative subtraction of the point-spread function (PSF) components at the positions of the lensed images, requires exceptional seeing and spatial sampling, generally not available with the 1.3 m telescope. Standard deconvolution algorithms also require superb data, and their uncertainties are not easy to understand. In this paper we present a qualitatively different approach. Using the optimal image subtraction algorithm described in detail by Alard & Lupton (1998), and generalized by Alard (1999) for the case of spatially variable kernel, it is now possible to match PSFs of two images without noise-amplifying division in Fourier space. Photometry on difference images is free of many complications associated with other methods.

In § 2 we describe observations. Section 3 contains a description of the method, with the details of this particular adaptation and photometry on subtracted images. We summarize the results in § 4, and discuss future plans in § 5.

2. OBSERVATIONS

All observations presented in this paper were made with the 1.3 m Warsaw telescope at the Las Campanas Observatory, Chile, which is operated by the Carnegie Institution of Washington. The “first-generation” camera uses a SITe 2048 $\times$ 2048 CCD detector with 24 $\mu$m pixels, resulting in a 0′417 pixel$^{-1}$ scale. Images of QSO 2237+0305 are taken in normal mode (still frame) at “medium” readout speed, with gain $7.1e^{-}$ ADU$^{-1}$ and readout noise $6.3e^{-}$. For details of the instrumentation setup, we refer the reader to Udalski et al. (1997).

To assure uniformity of the data sets, all observing sequences within the OGLE project are programmed and can be executed in batch mode. Good seeing is essential for
ground-based measurements of Huchra’s lens, independent of the photometric method. Therefore, observations are restricted to nights with seeing better than about 1.4′, preferably with low sky background. The median FWHM of the seeing disk was 1.3″ in the data presented here. The observing season for QSO 2237+0305 at LCO lasts from late April to mid December. In satisfactory weather conditions on a given night, two 4 minute exposures in the standard V photometric band are taken, shifted by a few arcseconds with respect to each other. This can be done typically once or twice per week without a significant slowdown of the primary program. In 1997, we obtained 80 points during the observing season. In 1998, QSO 2237+0305 was temporarily removed from the observing program, and there are only 19 points during that period. However, starting from 1999 we expect to get time coverage, comparable to the 1997 observing season.

The OGLE II data pipeline automatically detects newly collected frames and performs bias and flat-field corrections (Udalski et al. 1997). At this point, initially reduced frames can be passed to photometric reductions, provided that there is automated software for that purpose. We describe such software in §§ 3 and 5, along with the planned alert system for high-magnification events in QSO 2237+0305.

3. PHOTOMETRY

3.1. Image Subtraction and Difference Photometry

Systems such as Huchra’s lens pose a remarkable level of complication for ground-based photometry with medium seeing. Because of small image separations and their proximity to the galaxy nucleus, each pixel near the center of the blend contains light contributions from each of the four lensed components. Fainter, but complicated, light distribution from the underlying barred spiral only makes things worse, with the most significant contamination due to the galaxy core. In the OGLE data, the positions of all the lensed components fit within an area of about 25 pixels. Clearly, a full fit of positions and intensities is out of the question, even assuming that we knew the shape of the galaxy light distribution. The top panels of Figure 1 illustrate the observational situation. On the other hand, this extreme local crowding occurs in the field with a very low density of stars, which complicates the determination of the PSF, especially in the presence of spatial gradients. Therefore, the basic strategy adopted here is to fix as many parameters as possible and avoid fitting the galaxy light altogether by means of image subtraction. We subtract a reference image from each of the exposures and obtain a series of frames with only the variable part of the flux. This should completely remove the foreground galaxy and leave a blend of four variable components with known geometry, each of them PSF-shaped.

Some preliminary processing is required before one can subtract two images of the same stellar field. Both images must be resampled onto the same coordinate grid, and PSFs need to be matched. The first step is extracting a 250′′ × 500′′ field centered on the object. In this relatively small field, the spatial gradients of the PSF are not too large for a low-order fit, and at the same time the field contains enough stars to obtain a reliable subtraction. Stars are detected at maxima of the cross-correlation function with the approximate Gaussian model of the PSF. The cross-correlation image is done by convolving with the lowered Gaussian filter. For the coordinate transformation, we use a first-order fit to coordinates of about 12 stars found in both a given frame and the reference frame. A simple algorithm for detecting and removing cosmic rays is run before resampling the processed image to the coordinate system of the reference image. We use a bicubic spline interpolator to perform the resampling. At this stage, a resampled frame and the reference frame are fed to the main program, which calculates a spatially variable convolution kernel between both frames. This code utilizes a method newly developed by Alard & Lupton (1998). Further development of the method for spatially variable kernels (Alard 1999) is central to the application described in this paper for the reasons outlined above.

Briefly, if one decomposes the convolution kernel into N basis functions with constant shape, the problem reduces to a linear least-squares fit for the amplitudes of all kernel components. Convolutions of the reference image with each of the N kernel components become basis vectors and can be used to fit any other image of the same stellar field, provided it has been resampled to the coordinate grid of the reference image. The original method assumes that there are no spatial gradients of the PSF. Remarkably, this algorithm works best in crowded fields, where the majority of pixels contain information about the PSF. It can even treat some weak PSF gradients if we can afford subdividing the image into smaller pieces.

The implementation gets complicated when the above assumption of a constant kernel breaks down. In this case, the number of coefficients needed in order to fit spatial variation of the nth order is \((n + 1)[(n + 2)/2]\) larger than in the previous problem, and direct extension of the algorithm...
induces unrealistic computing requirements. However, by assuming that spatial variations of the kernel are negligible on the scale of the kernel size, one can reduce the most time-consuming calculation, that of elements of the least-squares matrix, to shuffling elements of the corresponding (much smaller) matrix from the previous problem with a constant convolution kernel.

We found that the constant part of the kernel solution was well described by three Gaussians with \( \sigma 0.7, 1.2, \) and 1.8 pixel, modified by polynomials of order 4, 3, and 2, respectively. We allow only first-order spatial variation of the kernel, since there are only nine stars that can be used in the fit. In the output, we have a subtracted image with the seeing of the currently processed frame and an intensity scale corresponding to the reference frame, plus the best-fit convolution kernel. In all difference images the residuals of constant stars were consistent with the photon noise of a single frame. The mean of about 20 frames with the best seeing and low sky background, resampled onto the same coordinate grid, is the correct choice for the reference image and allows us to approach the photon noise limit. We used the 18 best frames to obtain a good reference image, practically noiseless compared to a single exposure. In difference images, the galaxy is completely removed outside the region dominated by the lens, with residuals symmetric about zero and consistent with the photon noise. We believe that this is also the case inside this region. Figure 1 shows central parts of the reference image and typical test image, as well as the corresponding difference image and the best-fit PSF-matching kernel. Sample difference images from various epochs are shown in Figure 2. Variability of all quasar components is obvious.

The difference image contains only the variable part of the flux and can be used for high-precision relative photometry. After the galaxy is removed, remaining light can be modeled with four PSFs. The geometry of the lensed quasar images is known with a very high accuracy from Hubble Space Telescope (HST) data. We adopted positions relative to component A from Crane et al. (1991). In numerous difference frames, A was the only quasar image that significantly changed its brightness with respect to the reference frame. Therefore, the PSF component at the position of A, corresponding to the difference flux, was practically free of contamination by the remaining components of the blend. This simplified calculation of its centroid in a stack of 40 such frames and thus allowed us to obtain positions of all the lensed quasar images. The last step is a linear fit to the amplitudes of the four lensed components in the difference image. The area dominated by variable light and therefore useful for this purpose consists of pixels with centers not farther than 2.4 pixel from any of the quasar images. We modeled the first-order spatial variation of the PSF in the reference image using the code written for the DENIS survey (C. Alard 1999, in preparation). For any other frame (and difference image), the PSF is calculated simply by convolving the reference PSF with the best-fit PSF matching kernel at the position of the measured object.

3.2. Uncertainties in Difference Photometry

Errors of the individual photometric points were estimated by propagating the photon noise through the linear least-squares fit and adding in quadrature a correction for uncertain flat-fielding at the level of 1% of the mean amplitude of the A component. This simple noise model gives error bars consistent with the scatter of the individual measurements.

Given the relative complexity of the method and the source, we investigated possible systematic effects in our photometry. The main test was to measure several simulated microlensing events generated by adding flux to one of the quasar components in real images. The PSF required for that purpose was calculated separately for each frame before resampling to the reference coordinates. Therefore, the PSF did not depend on the reference frame or the information obtained with the image-subtraction software (the PSF matching kernel). The photon noise was included in these simulations. In each of our fake events, a single quasar component undergoes a brightening by about 1.0 mag in the middle of the first observing season. The FWHM timescale of events was about half the duration of the first season, and the flux added to real frames was approaching 0 near the beginning and the end of the season. We ran the modified images through exactly the same reductions as the original ones and compared the flux differences between the two sets of measurements with the input values. The results were very encouraging. In all cases, the software correctly recovered the flux used in the modified frames; there were no significant correlations between the calculated fluxes for quasar components A–D, and the scatter was consistent with our noise estimates.

As an additional check, we looked for possible correlations between the deviations of the individual measurements from the mean trend and the seeing or the sky background level. We find no significant correlation with the seeing. Most likely, this is attributable to the fact that our measurements of QSO 2237+0305 are restricted to nights with very good seeing, and given the lower bound set by the instrument/dome, the FWHM of the seeing disk is confined to a very narrow 1'2–1'4 range. There is a trace of some weak correlation with the sky background. This is simply the uncertainty in the flat field, mentioned at the

Fig. 2.—Sample of nine difference images of the QSO 2237+0305 at various epochs from the OGLE data. North is up and east is to the left.
beginning of the section, which is slightly more likely to manifest itself when the background level is high. Nevertheless, with the high-background frames rejected, the flat-field contribution to the measurement error is practically random, and we include it in our error estimate.

In conclusion, the systematics in our difference photometry are small compared to the random errors.

3.3. Zero Point Calibration

The procedure described in the previous paragraph gives only a variable part of the flux, e.g., in counts per second. Putting the light curve on a magnitude scale requires knowing the absolute amplitude of all components and a reference star in at least one image. In the presence of the intervening galaxy, this requires a reasonably good model of the underlying light distribution.

We used public HST images from the archive at STScI. The images were taken on 1995 June 23 with the WFPC2 using the F555 filter, centered on \( \lambda = 5407.0 \) Å, the closest available band to \( V \). The proposal ID is 5236. Four of the images had exposure times of 200 s, and one was exposed for 800 s.

The galaxy template was prepared by symmetrization with respect to the brightest pixel. In the annulus contaminated by quasar images, symmetric pairs of pixels are examined, and the lower of the two is adopted as the best guess for the value of both pixels, with 0.6 \( \sigma \) correction for the bias due to minimization. This simplified version of the symmetrization technique used by the SDSS survey for deblending star and galaxy images (R. H. Lupton 1999, in preparation) effectively removes quasar components A and B; however, it fails for C and D, due to their very symmetric position with respect to the galaxy nucleus. Fortunately, in WFPC2 images the galaxy is smooth on a much larger scale than the area occupied by any of the quasar images. It is possible to make a local fit to the galaxy light and subtract the faintest image before symmetrization, which solves the problem.

The galaxy template must be rotated, resampled to the pixel grid of the OGLE reference frame, and degraded to the seeing of each OGLE test frame before the fit. We fitted a model consisting of four PSFs and the galaxy template to every image in our data set. This is much like the conventional approach, except that in the process we used PSF-matching kernels obtained with the image-subtraction software. The scatter of this photometry was about a factor of 2 larger than in the image-subtraction method. Nevertheless, the weighted mean of the difference between the two light curves (in counts) is the desired amplitude of a given quasar component in the reference image. The statistical quality of our zero point is about 2\%, 3\%, 8\%, and 13\% for components A, B, C, and D, respectively; therefore, it is much worse than the accuracy of the difference signal with respect to the reference frame. The data were reduced to the standard \( V \) magnitudes based on observations of standard stars from selected fields of Landolt (1992) obtained on 11 photometric nights. We get \( V = 17.466 \pm 0.018 \) and \( 18.138 \pm 0.021 \) mag for stars \( \alpha \) and \( \beta \) of Corrigan et al. (1991), brighter by only about 0.038 mag compared to the photometry obtained indirectly by these authors.

4. RESULTS

Figure 3 shows the light curve of QSO 2237+0305. Photometric data plotted in Figure 3 can be obtained from the OGLE web page. The fifth-order polynomial fits to light variations are also shown to guide the eye. All components display significant variations, especially between the two observing seasons, and even more importantly, all of them varied differently. The 18.14 mag reference star measured using exactly the same method was constant within the errors, which confirms that our photometry is correct (Fig. 3). Independent \( g \)-band photometry with the 3.5 m telescope at the Apache Point Observatory in New Mexico is fully consistent with our observations (E. L. Turner 1999, private communication). Component C brightened by as much as 0.7 mag and actually almost changed place in brightness with B. The simplest explanation of these phenomena is microlensing in the bulge of the macrolensing galaxy. For the first time we see it happening, in the sense that smooth variation of source amplification is observed, most striking for component A. Wambsganss, Paczynski, & Schneider (1990) demonstrated the huge diversity of possible light variations produced by a complicated network of clustered microcaustics and showed that the sharpest features present in the light curve are directly related to the size of the source, the masses of the microlenses, and the transverse velocity. They also stressed that frequently sampled light curves should constrain some of these unknowns. Witt & Mao (1994) noticed that in the early 1990s, images C and D were relatively quiescent and probably dimmed in the \( V \) band, based on their macrolens models. This might explain why image C brightened and not otherwise. In the present paper we do not attempt any further theoretical interpretation of the data.

6 Ogle web page is available at: http://www.astrouw.edu.pl/~ftp/o!gle, and its USA mirror, http://www.astro.princeton.edu/~ogle.

![Fig. 3.—Light curve of the QSO 2237+0305. Also shown is the light curve of the 18.14 mag reference star, shifted by 1.1 mag for clarity. The polynomial fits help to assign the photometric points to each of the components.](image)
It must be emphasized that difference photometry with respect to the reference image is very accurate; however, the overall normalization of the light curve can be off by 15% for the faintest component. On a magnitude scale this affects the shape of the light curve as well, since for any test image we have

$$m_V = \text{const} - 2.5 \log \left( \frac{f_{V,\text{ref}} + \Delta f_V}{\text{norm}} \right) \text{ mag}.$$  

In this equation, the difference flux $\Delta f_V$ is known with high precision, but the amplitude of a given component in the reference frame $f_{V,\text{ref}}$ is known less accurately. For some applications it may be safer to go back to the linear scale and obtain a zero-point–free shape of the light curve. This is accomplished, for instance, if we express flux density in mJy ($10^{-29}$ W m$^{-2}$ Hz$^{-1}$):

$$f_V = f_{V,\text{ref}} + \Delta f_V = 3.67 \times 10^{-(0.4m_V+6)} \text{ mJy},$$

as has been done in Figure 4.

5. DISCUSSION AND FUTURE PERSPECTIVE

We demonstrated that good-quality monitoring of QSO 2237+0305 is possible with a 1.3 m telescope. Despite the fact that complications characteristic of both crowded and sparse fields are present, photometry of this system is well handled by the image-subtraction method of Alard & Lupton (1998) and Alard (1999), supplemented with PSF fitting of the difference image. Resulting light curves are significantly better than any other preexisting measurements, even with much larger instruments. Probably the most important improvement is due to much better time coverage, especially during the 1997 observing season. Starting from 1999, we expect to obtain similar light curves during the entire period when this object is accessible from LCO. It is likely that the zero point will be improved in the future using overlapping observations from instruments with better seeing and/or a better galaxy template.

All data processing described in § 3 has been integrated to the level at which it is possible to run reductions automatically once a new image is collected and simply wait for the new point to be added to a postscript plot. The photometric pipeline consists of several stand-by programs for each step of reductions, controlled by a shell script. It is planned that this software will become a part of the OGLE photometric pipeline at LCO. This will provide an easy way of checking the state of Huchra’s lens in real time, and therefore we should be able to detect caustic crossings early enough to issue an alert. Caustic crossing provides in principle the way to spatially resolve the source, which in this case would place a very tight limit on the size of the quasar (Wambsganss et al. 1990). For this measurement it is essential to get good coverage of a high-amplification event, with larger instruments and better instrumental seeing if possible; therefore, the importance of early detection of high-amplification events cannot be overestimated. Up-to-date information on Huchra’s lens is available from the OGLE web page.\footnote{Ogle web page is available at: http://www.astrouw.edu.pl/~ftp/ogle, and its USA mirror, http://www.astro.princeton.edu/~ogle.}

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FIG. 4.—Same as Fig. 3, but in mJy. Note that the amplitudes of microlensing events in this linear plot are free of the uncertainties associated with the zero point. The flux of the reference star has been lowered by 0.165 mJy for clarity.