The Optical Gravitational Lensing Experiment. OGLE-III Long Term Monitoring of the Gravitational Lens QSO 2237+0305

A. Udalski, M. K. Smyński, M. Kubiał, G. Pietrzyński, I. Sośniski, K. Żebrań, O. Siewczyk, Ł. Wyrzykowski, K. Ulaczyk and T. Węckowski

Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland

E-mail: (udalski,msz,mbkpietrzyn,soounsk,zebrun,siewczyk,wyrzykow,kulaczyk,twieck)@astrouw.edu.pl

ABSTRACT

We present results of the long term monitoring of the gravitational lens QSO 2237+0305 conducted during the OGLE survey. Light curves of all four components of the lens obtained during the second phase of the OGLE project (OGLE-II; 1997–2000) are supplemented with the data collected in the OGLE-III phase in the observing seasons 2001–2006. Calibration procedures to tie the new OGLE-III data with already calibrated OGLE-II light curves are described. The resulting homogeneous OGLE data set is the most extensive photometric coverage of the gravitational lens QSO 2237+0305, spanning now one decade – the seasons from 1997 to 2006 – and revealing unique microlensing activity of this spectacular object.

All photometric data of the gravitational lens QSO 2237+0305 collected by OGLE are available to the astronomical community from the OGLE INTERNET archive.

1 Introduction

The gravitational lens QSO 2237+0305 called also Huchra’s lens (Huchra et al. 1985) or the Einstein Cross is a spectacular object consisting of four, separated by about 1” in the sky, images of a distant quasar (z = 1.7) and a nearby barred spiral galaxy (z = 0.04) that acts as a gravitational lens. Favorable positioning of the quasar and galaxy should potentially produce prominent microlensing effects in the light curve of the quasar images (Schneider et al. 1988) and indeed such effects were discovered by Irwin et al. (1989). Due to the magnitude of microlensing variability the 2237+0305 lens became the crucial object for testing the models of the source and mass distribution in the lensing galaxy and our understanding of extragalactic microlensing (e.g., Wambsganss, Paczyński and Schneider 1990, Rauch and Blandford 1991, Jaroszyński, Wambsganss and Paczyński 1992, Wyithe, Webster and Turner 2000a, Yonehara 2001, Wisotzki et al. 2003, Kochanek 2004, Jaroszyński and Skowron 2006 and many others).

Although it was soon realized that for constraining the models long term, well sampled monitoring of the object is necessary, the photometric data of 2237+0305 remained sparse until the end of 1990s. Typical light curve contained only a few epochs...
per season and covered at most five observing seasons (Corrigan et al. 1991, Østensen et al. 1996). One of the reasons were difficulties in measuring with reasonable accuracy the magnitudes of lens components because of significant blending due to their proximity in the sky and background of the lensing galaxy. Only observations obtained at observing sites with very good seeing could be useful.

The situation has significantly improved when the Optical Gravitational Lensing Experiment (OGLE) started regular monitoring of the 2237+0305 lens as a subproject of the second phase (OGLE-II) of this long term photometric survey (Woźniak et al. 2000a). Regular – every few nights – observing pattern of 2237+0305 combined with the newly developed algorithm of data reduction based on the image difference technique (DIA: Alard and Lupton 1998, Alard 1999, Woźniak 2000), that turned out to be very successful and allowed precise determination of magnitudes of all four components, produced unique new generation light curves of the 2237+0305 lens images. When the data reduction algorithm was implemented at the OGLE telescope to allow real time photometric monitoring of 2237+0305 (1998) it became possible to start hunting for the detection of high magnification events in the microlensing variability (Woźniak et al. 2000b). Such rare events, in particular the caustic crossing which should occur every few years, are very important for mapping the distribution of light of the lensed quasar.

From the end of 1990s two other groups also monitored the 2237+0305 lens simultaneously with OGLE. Complementary to OGLE but less extensive data sets were obtained by the CLITP project (Alcalde et al. 2002) from Canary Islands and by Vakušlik et al. (2004) and Koptelova et al. (2004) from Majdanak Observatory.

The OGLE-II monitoring of the 2237+0305 lens ended at the end of 2000 and the OGLE-II light curves covered four observing seasons: 1997–2000. When the OGLE-III phase (Udalski 2003) started regular observations in 2001, the 2237+0305 lens was again included to the list of monitored targets. In this paper we describe the collected OGLE-III data of 2237+0305 as well as the reduction and calibration procedures. The main goal of this paper is to provide the astronomical community with unique homogeneous calibrated light curves of the 2237+0305 lens images covering at present ten observing seasons from 1997 to 2006.

## 2 Observational Data

Observations presented in this paper were collected with the 1.3-m Warsaw telescope at the Las Campanas Observatory, Chile (operated by the Carnegie Institution of Washington), equipped with a wide field CCD mosaic camera. The camera consists of eight 2048 × 4096 pixel SITe ST002A detectors. The pixel size of each of the detectors is 15 µm giving the 0″26/pixel scale at the focus of the Warsaw telescope. Full field of view of the camera is about 35″ × 35″. The gain of each chip is adjusted to be about 1.3 e−/ADU with the readout noise of about 6 to 9 e−, depending on the chip.

The typical observing season of 2237+0305 from the Las Campanas Observatory lasts for about 8 months, starting at the end of April and ending in mid December each year. Because of very small separation of the 2237+0305 images strong seeing limits are imposed on the collected images. The upper limit of acceptable seeing is 1″5. Each observation of 2237+0305 consists of two exposures to have two independent measurements of brightness for each epoch to check consistency. The position of the lens is shifted by about 15″ between these exposures to avoid accidental putting the object on a defect on the chip. Also repeating the exposures ensures at least one good measurement in the case of a hit of the lens by a cosmic ray.
The lens is always placed in the middle of chip #3 of the OGLE mosaic camera. Observations are obtained through the V-band filter and the exposure time is 360 seconds. 2237+0305 is monitored every 3–5 nights, weather permitting. If the brightness of any component starts rising fast, observations are made more frequently, sometimes even every night. The first two observing seasons – 2001 and 2002 – contain fewer observations. Although the 2237+0305 lens was included to the OGLE targets from the very beginning, the OGLE-III project started regular observations in mid June 2001 – well in the 2237+0305 observing season. In the 2002 season the 2237+0305 lens was observed rarely due to some technical problems.

3 Data Reductions

Collected images of 2237+0305 are de-biased and flatfielded at the telescope by the regular OGLE-III pipeline (Udalski 2003). Then they are fed into the main reduction pipeline which includes a separate procedure for deriving photometry of 2237+0305. It is based on the image difference technique, DIA, and is very similar to the OGLE-III standard reductions of relatively empty fields in the LMC and SMC halos. In the case of 2237+0305 lens only a 2048 × 2048 pixel subframe centered on the lens is photometrically reduced. Although the 2237+0305 field is very empty, such a subframe contains about 50 stars – sufficiently enough to derive accurate transformations between reduced and reference images: astrometric transformation for resampling the reduced image to the common (X, Y) grid and PSF transformation for image subtraction. The reference image of 2237+0305 is constructed from 18 individual, best seeing images. A subframe of this image showing the lensing galaxy and four quasar images is shown in Fig. 1.

![Fig. 1.](image)

After image subtraction the remaining signal contains information on the variability of components. We measure these differential fluxes with PSF photometry fitting simultaneously four profiles centered at fixed position of each component derived from the HST image, similar as in Woźniak et al. (2000a). Photometry is also obtained at the position of a few reference stars. To obtain the absolute flux of each measured object the difference signal must be added to the reference image flux. For constant stars this flux is measured with PSF fitting program (DoPHOT) and converted to the
DIA flux scale. However, the 2237+0305 components cannot be reliably measured in the standard way in the reference image due to large and non-uniform background of the lensing galaxy. Therefore the reference fluxes of the 2237+0305 components must have been derived in other way (Section 4).

Finally, the measured absolute fluxes of our objects were converted to magnitudes and shifted to the calibrated magnitude scale by adding a zero point based on the known $V$-band magnitudes of reference stars and stored in the standard OGLE database of the 2237+0305 field.

### 4 Calibration and Tests of the Photometry

Although during the observing seasons 2001–2003 observations of 2237+0305 were regularly carried out, the collected images had to wait for photometric reductions until the significant sample of good seeing frames, potential components of the reference image, was secured. It is crucial to achieve the best photometric accuracy to stack about 10–20 best seeing images when building the reference image. After 2003 season the dataset was complete enough that a good quality reference image could be made and the DIA photometry of already collected data could be derived. Since the beginning of 2004 season the real time data system was installed at the telescope for on-line reductions of the 2237+0305 observations.

While it was easy to tie the magnitude scale of the OGLE-III photometry of stars in the field of 2237+0305 to the standard photometry scale obtained during the OGLE-II phase based on non-variable comparison stars (Woźniak et al. 2000a), the determination of magnitudes of the lens components required information on their reference image fluxes – the values unknown a priori and very difficult to measure because of small angular components separation and large background of the overlapped lensing galaxy. The DIA photometry only provides precise difference fluxes between measured and reference images.

Contrary to non-variable stars the reference fluxes of the lens components were certainly different than those used during OGLE-II monitoring (after matching both photometric scales). Because the four images of 2237+0305 are highly variable, their flux values in the reference image constructed from 2001–2003 frames must have been different than those in the OGLE-II reference image from 1990s. On the other hand, the lens components fluxes in OGLE-II reference image and, thus, the entire OGLE-II photometry were calibrated to the standard $V$-band scale by Woźniak et al. (2000a).

Unfortunately, there was more than half a year gap between the last OGLE-II and first OGLE-III observations so it was not possible to compare almost simultaneous observations from both OGLE observing set-ups and to tie both photometries of the lens. Therefore, as the first approximation we extrapolated the observed OGLE-II light curves of each lens component to the epoch of the initial OGLE-III observations of the 2237+0305 lens. Then, we used these extrapolated, calibrated magnitudes to derive the necessary OGLE-III reference image fluxes of each component that produced identical as OGLE-II magnitudes for the initial OGLE-III images. However, such an approach was only a crude approximation of the OGLE-III magnitude scale of lens images and its accuracy highly depended on the unknown variability of the lens components during the eight months gap in observations between OGLE-II and OGLE-III phases. Nevertheless, we decided to make our photometry publicly available at that moment. The general shape of the light curve was in any case preserved so the main goal of the real time monitoring system – prompt detection of rapid brightness changes could have been achieved. Up to the end of the 2006 observing season the OGLE-III data posted on the 2237+0305 OGLE WWW page used this preliminary calibration.
It is obvious that the application of the unique OGLE observations of 2237+ 0305 to any scientific project requires much more precise calibration. In particular, it is very important that both OGLE-II and OGLE-III data sets are accurately tied photometrically to each other making one homogeneous data set covering now ten seasons. Therefore, we applied the following procedure. First, we assumed that the calibration of OGLE-II magnitudes of the lens components (Woźniak et al. 2000a) is correct and we did not attempt to independently recalibrate these zero points. To tie the OGLE-II and OGLE-III 2237+0305 photometries we decided to reduce a sample of the best seeing OGLE-II images of 2237+0305 with the OGLE-III data pipeline, that is with the OGLE-III reference image with provisional approximate calibration of the lens fluxes. Because the calibrated magnitudes of components are known for this sample from OGLE-II dataset, the results of new reductions of the sample with OGLE-III reference image can be used to readjust OGLE-III reference fluxes of the lens and to tie both datasets.

It is also worth mentioning that such an approach simultaneously provided a test of reliability of OGLE reductions of 2237+0305 and observed features in the light curves. Because the new reductions of a sample of OGLE-II images must have been done with completely different OGLE-III reference image, different version of the DIA software and required special preparation of the OGLE-II frames, the consistency of the new reductions with the original light curves would provide strong argument that the observed light variations are real, not of instrumental/reduction origin.

We selected a sample of 36 best seeing frames of 2237+0305 collected during OGLE-II after HJD=2 451 110. The position of 2237+0305 on earlier images was shifted so that the OGLE-II field would only partially overlap with the OGLE-III reference image lowering the already small number of field stars necessary for the DIA image transformations. The selected OGLE-II images required special preparation before running through the OGLE-III data pipeline. First they had to be cleaned from cosmic ray hits and then rotated by $\approx 90^\circ$, flipped and resampled to the OGLE-III image scale (from 0\textquoteleft\textquoteleft42/pixel in OGLE-II to 0\textquoteleft\textquoteleft26/pixel in OGLE-III). Resampling was performed using flux conserving interpolation with bicubic splines. Due to the necessity of resampling of the OGLE-II images to the finer resolution grid we limited our calibrating OGLE-II images only to those with the best resolution (seeing $< 1\arcsec 25$).

| Image | Flux       |
|-------|------------|
| A     | 66794 ± 1043 |
| B     | 16828 ± 978  |
| C     | 24099 ± 1624 |
| D     | 13417 ± 921  |

After running the OGLE-II images through the OGLE-III pipeline we compared the OGLE-II calibrated magnitudes (Woźniak et al. 2000a) with new OGLE-III pipeline photometry and for each lens component and each OGLE-II image we derived the corrected OGLE-III reference image flux. Fig. 2 presents the results as a function of time. It can be seen that the results are very consistent – the new OGLE-III reference image flux of each lens component is, within the errors, constant over the time. The average values of these, now calibrated to OGLE-II scale, fluxes are listed in Table 1.
Fig. 2. OGLE-III reference image flux of each of the components of 2237+0305.

Accuracy of their determination varies from about 2% for the brightest image A to about 7% for the faintest image D. The magnitude of each component can be derived from Eq. (1). This is a prescription how to rescale OGLE-III data if the fluxes from Table 1 (that is the Wozniak et al. (2000a) calibration) were again recalibrated.

\[ V = -2.5 \cdot \log(\text{Difference_flux} + \text{Reference_flux}) + 29.20. \]  

Fig. 3 shows the original OGLE-II light curves of 2237+0305 components (small dots) with superimposed photometry of our sample of OGLE-II best seeing images processed with the OGLE-III pipeline (large dots). It is clear that the agreement and consistency of both light curves is very good indicating that with the OGLE-III reference image fluxes from Table 1 the OGLE-III photometry of 2237+0305 is now in the calibrated OGLE-II scale. Also, remarkable agreement of the shape of light curves from both completely independent reductions of OGLE-II images strongly indicates that the measured variations of brightness of 2237+0305 are real.
Finally, as the last step we converted the provisionally calibrated photometry of 2237+0305 components collected during the entire OGLE-III observing period (2001–2006) to the calibrated OGLE-II scale recalculating the magnitudes using the calibrated reference image fluxes from Table 1. In this way we obtained one homogeneous dataset covering the years 1997–2006. Table 2 presents calibrated photometry of 2237+0305 images and two reference stars (Woźniak et al. 2000a) collected during OGLE-III. Only several first observations are listed as an example – the full Table is available electronically from the OGLE WWW archive – see Section 6. It is regularly updated during the observing season when new observations are collected. Also OGLE-II photometry is available from this site.
OGL-III photometry of the QSO 2237+0305 gravitational lens (sample)

| HJD 2450000 | A     [mag] | B     [mag] | C     [mag] | D     [mag] | C1    [mag] | C2    [mag] |
|-------------|------------|------------|------------|------------|----------|----------|
| 2085.89230  | 17.028±0.007 | 18.588±0.021 | 18.051±0.014 | 18.747±0.020 | 17.412±0.005 | 18.160±0.008 |
| 2085.89738  | 17.013±0.006 | 18.538±0.022 | 18.053±0.015 | 18.884±0.024 | 17.403±0.005 | 18.170±0.008 |
| 2091.89157  | 17.024±0.005 | 18.536±0.014 | 18.062±0.010 | 18.777±0.014 | 17.409±0.004 | 18.181±0.006 |
| 2091.90025  | 17.029±0.006 | 18.569±0.015 | 18.079±0.011 | 18.832±0.015 | 17.407±0.004 | 18.177±0.007 |
| 2103.81800  | 17.052±0.005 | 18.529±0.013 | 18.061±0.010 | 18.764±0.012 | 17.400±0.004 | 18.155±0.007 |
| 2103.82308  | 17.057±0.005 | 18.479±0.012 | 18.061±0.009 | 18.784±0.011 | 17.395±0.004 | 18.156±0.007 |

5 Discussion

Calibration of the OGLE-III observations of 2237+0305 described in the previous Section indicates that the provisional calibration presented in OGLE WWW archive in years 2004–2006 was relatively accurate to several percent for images A, B and C. The largest discrepancy occurred for image D that showed a steep rise of brightness in the end of 2000 OGLE-II season leading to overestimated extrapolated magnitude for the beginning of the 2001 OGLE-III season. Fortunately this image was relatively quiet during the further OGLE-III monitoring.

The test of accuracy of the method of reduction of 2237+0305 is reassuring that the features observed in the derived light curves are real. Fig. 3 clearly shows that in spite of different reference images, different pixel sampling of observations, orientation of the object on the chip, different reduction software etc., the light curve features remain practically identical. Thus, one can be confident that the entire light curve represents the real variation of brightness of the 2237+0305 images. Similar shape of the light curves of 2237+0305 images was also obtained by Alcalde et al. (2002) and Koptelova et al. (2004) in the overlapping period of observations even though these observations were obtained through a different filter.

Fig. 4 presents the entire light curve of all four components of 2237+0305 covering one decade of OGLE observations: 1997–2006. This is the most extensive existing photometric dataset of 2237+0305 showing complex long term variability of this unique object. The light curves of each image reveal large brightness variations in the time scale of months and years. The largest brightenings are certainly caused by microlensing activity. However, part of the variability can probably be also attributed to the long time variation of the quasar brightness. The time delay of 2237+0305 is believed to be very short (Wambsganss and Paczyński 1994, Dai et al. 2000b, Gil-Merino et al. 2006). The remaining images B and D, while showed considerable variability, varied in longer time scales.
Fig. 4. OGLE light curve of the gravitational lens QSO 2237+0305 covering ten observing seasons 1997–2006.
Images B, C and D were relatively quiet during the first years of OGLE-III monitoring while image A showed a $\approx 0.5$ mag variability in long time scale. The most spectacular changes occurred during the last three observing seasons. First, the image B started brightening again and after the rise by about 1 mag, became again the second brightest one (maximum at HJD$'\approx 3500$). On the other hand the image A began to increase its brightness in the middle of the 2005 season and brightened continuously in the first part of the 2006 season. The rising was so rapid that at some moment it suggested an approach to the caustic. However, it slowed down in the first months of the 2006 season leading to a peak at HJD$'\approx 3900$. Nevertheless, the brightness remained at similar high level during the next months. In the second part of the 2006 season image A started brightening again. End of the 2006 season prevented further observations of this extremely interestingly developing episode. It will be, then, crucial to collect the first observations of 2237+0305 as soon as possible in April 2007.

Although the variability of all images of 2237+0305 during the last decade showed remarkable events, there was no clear and unambiguous evidence of the caustic crossing in any of the images. Theoretical predictions indicate that in similar time scales of the OGLE monitoring one could expect occurrence of at least one such event (Wyithe, Webster and Turner 2000c). Thus, the hunt for the caustic crossing in 2237+0305 (Woźniak et al. 2000b) still remains the most important goal of the further monitoring of 2237+0305. The OGLE survey plans to continue similar coverage of this gravitational lens during the next observing seasons.

6 Data Availability

The photometric data of OGLE-III monitoring of 2237+0305 are available in the electronic form from the OGLE archive:

\url{http://ogle.astrouw.edu.pl/ogle3/huchra.html}
\url{ftp://ftp.astrouw.edu.pl/ogle/ogle3/huchra}

During the observing season (April–December) the light curves are updated regularly after each observation providing real time monitoring of the gravitational lens QSO 2237+0305.

Acknowledgements. The paper was partly supported by the Polish MNiSW DST grant to Warsaw University Observatory. Partial support to the OGLE project was provided with the NSF grant AST-0607070 and NASA grant NNG06 GE27G to B. Paczyński.

REFERENCES

Alcalde, D., et al. 2002, Astrophys. J., 572, 729.
Corrigan, R.T., et al. 1991, Astron. J., 102, 34.
Dai, X., Chartas, G., Agol, E., Bautz, M.W., and Garmire, G.P. 2003, Astrophys. J., 589, 100.
Jaroszyński, M., Wambsganss, J., and Paczyński, B. 1992, Astrophys. J. Letters, 396, L65.
Jaroszynski, M., and Skowron, J. 2006, Acta Astron., 56, 171.
Gil-Merino, R., González-Cadeno, J., Goicoechea, J.I., Shalypin, V.N., and Lewis, G.F. 2006, MNRAS, 371, 1478.
Huchra, J., Gorenstein, M., Horine, E. Kent, S., Perley, R., Shapiro, I.I., and Smith, G. 1985, Astron. J., 90, 691.
Irwin, M.J., Webster, R.L., Hewett, P.C., Corrigan, R.T., and Jedrzejewski, R.I. 1989, Astron. J., 98, 1989.
Kochanek, C.S. 2004, Astrophys. J., 605, 58.
Koptelova, E., Shimanovskaya, E., Artamonov, B., Sazhin, M., Yagola, A., Bruevich, V., and Burkhanov, O. 2004, MNRAS, 356, 323.
Koptelova, E., Oknyanskiy, V.L., and Shimanovskaya, E.V. 2006, Astron. Astrophys., 452, 37.
Østensen, R., et al. 1996, Astron. Astrophys., 309, 59.
Rauch, K.P., and Blandford, R.D. 1991, Astrophys. J. Letters, 381, L39.
Schneider, D.P., Turner, E.L., Gunn, J.E., Hewitt, J.N., Schmidt, M., and Lawrence, C.R. 1988, Astron. J., 95, 1619.
Udalski, A. 2003, Acta Astron., 53, 291.
Vakulik, V.G., et al. 2004, Astron. Astrophys., 420, 447.
Wambsganss, J., Paczyński, B., and Schneider, P. 1990, Astrophys. J. Letters, 358, L33.
Wambsganss, J., and Paczyński, B. 1994, Astron. J., 108, 1156.
Wisotzki, L., Becker, T., Christensen, L., Helms, A., Jahnke, K., Kelz, A., Roth, M.M., and Sanchez, S.F. 2003, Astron. Astrophys., 408, 455.
Woźniak, P.R., Alard, C., Udalski, A., Szymański, M., Kubiak, M., Pietrzyński, G., and Zębruń, K. 2000a, Astrophys. J., 529, 88.
Woźniak, P.R., Udalski, A., Szymański, M., Kubiak, M., Pietrzyński, G., Sozzański, I., and Zębruń, K. 2000b, Astrophys. J. Letters, 540, L65.
Wyithe, J.S.B., Webster, R.L., and Turner, E.L. 2000a, MNRAS, 318, 762.
Wyithe, J.S.B., Webster, R.L., and Turner, E.L. 2000b, MNRAS, 318, 1220.
Wyithe, J.S.B., Webster, R.L., and Turner, E.L. 2000c, MNRAS, 315, 337.
Yonehara, A. 2001, Astrophys. J. Letters, 548, L127.