OGLE 2003-BLG-235/MAO 2003-BLG-53: A PLANETARY MICROLENSING EVENT

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ABSTRACT

We present observations of the unusual microlensing event OGLE 2003-BLG-235/MAO 2003-BLG-53. In this event, a short-duration (~7 days) low-amplitude deviation in the light curve due to a single-lens profile was observed in both the MOA (Microlensing Observations in Astrophysics) and OGLE (Optical Gravitational Lensing Experiment) survey observations. We find that the observed features of the light curve can only be reproduced using a binary microlensing model with an extreme (planetary) mass ratio of 0.0039±0.007 for the lensing system. If the lens system comprises a main-sequence primary, we infer that the secondary is a planet of about 1.5 Jupiter masses with an orbital radius of ~3 AU.

Subject headings: gravitational lensing — planetary systems — stars: individual (MAO 2003-BLG-53, OGLE 2003-BLG-235)

1. INTRODUCTION

Gravitational microlensing occurs when a foreground object passes through or very near the line of sight of a background source star, generating a well-known symmetric light-curve profile. If the foreground lens object is a star with an orbiting planet, then the presence of the planet may be detectable via a brief disturbance in the single-lens light curve (Mao & Paczynski 1991; Gould & Loeb 1992). This effect can potentially be utilized to detect planets with masses ranging from those of gas giants right down to terrestrial planets (Bennett & Rhie 1996).

The short timescales of these deviations, ranging from a few days for giant planets to hours for terrestrial planets, and their unpredictability present considerable challenges in any observational program. While some encouraging results have been obtained (Bennett et al. 1999; Albro et al. 2000; Rhie et al. 2000; Bond et al. 2002; Jaroszyński & Paczyński 2002), no firm detections of planets by microlensing have been obtained previously.

In this Letter, we report observations, obtained by OGLE (Optical Gravitational Lensing Experiment) and MOA (Microlensing Observations in Astrophysics), of the event OGLE 2003-BLG-235/MAO 2003-BLG-53 (hereafter O235/M53) that was independently detected in both survey programs. We observed a 7 day deviation that was strongly detected in both surveys. We show that an extreme mass ratio binary microlensing model best reproduces the observed features in the light curve.

2. OBSERVATIONS

Presently, Galactic bulge microlensing events are discovered and then reported by the two independently operating survey groups OGLE (Udalski 2003) and MOA (Bond et al. 2001). The microlensing event OGLE 2003-BLG-235 (α = 18°05′16.5″, δ = −28°53′42.0″, J2000.0) was first identified and reported by the OGLE Early Warning System (Udalski 2003) on 2003 June 22. It was independently detected by MOA on 2003 July 21 and reported as MOA 2003-BLG-53.

OGLE observations were carried out with the 1.3 m Warsaw telescope at Las Campanas Observatory, Chile, which is operated by the Carnegie Institute of Washington, equipped with a mosaic CCD camera with 8192 × 8192 pixels. The images were obtained in the J band with an exposure time of 120 s each. The observations presented here come from the OGLE-III phase of the OGLE survey and started in 2001 August. Additional photometry of the star was also collected during the OGLE-II phase (1997–2000). This data set, however, indicates no variability of the object during that period and was not used in further analysis.

MOA observations were carried out from the Mount John Observatory in New Zealand with a 0.6 m telescope equipped with a mosaic CCD camera with 4096 × 6144 pixels. The MOA images were obtained using 180 s exposures with a broadband red filter with its throughput centered on the standard I band.
As well as regular monitoring in the $I$ band, several $V$-band observations were obtained by OGLE at various magnifications of the event. These were not used in the microlensing modeling, but they were used to constrain the source and lens star properties. By plotting the linearized fluxes in the $I$ and $V$ bands against each other, a model-independent measurement of the color index of the source star was determined. We obtained $V-I = 1.58 \pm 0.02$. Using $E(V-I) = 0.82$ mag for the interstellar reddening toward the source (Sumi 2004), the corrected color index of $(V-I)_0 = 0.76 \pm 0.02$ indicates a G-type source star.

3. LIGHT-CURVE MODELING

The modeling of the observed light curve of O235/M53 was performed independently by three groups using different methods to generate numerical binary microlensing light curves (Bennett & Rhie 1996; Mao & Loeb 2001; Rattenbury et al. 2002), and all three found the solution that is presented in Figure 1. The observable quantities for all microlensing events are the Einstein radius crossing time $t_0$, the impact parameter $u_0$ (in Einstein radius units) of the source star trajectory with respect to the lens center of mass, and the time $t_0$ of the closest approach to the center of mass. For binary microlensing events, one also measures the mass ratio, $q \equiv M_s/M_L$, the transverse separation, $a$, of the lens components, and the position angle, $\phi$, of the binary with respect to the source-lens transverse velocity. For caustic crossing events, one also measures the ratio, $\rho \equiv \theta_a/\theta_E$, of the apparent angular radius of the source star to that of the Einstein ring. In addition to these seven physical parameters, there are two linear scaling parameters between the magnification and the flux units for each passband, giving a total of 11 parameters for the modeling. In our modeling procedure, we searched for local $\chi^2$ minima using minimization procedures that allowed all 11 parameters to vary simultaneously. Our light-curve modeling also employed a surface limb-darkening profile appropriate for a G-type star assuming a metallicity that is approximately solar.

TABLE 1

| Model      | $M_s/M_L$ | $\theta_a/\theta_E$ | $a/r_E$ | $\phi$ (deg) | $u_0$ | $t_0$ (days) | $I_{\text{source}}$ (mag) | $\chi^2$ (1267 dof) | $\chi^2_{\text{OGLE}}$ (178 dof) |
|------------|-----------|---------------------|--------|--------------|-------|-------------|--------------------------|----------------|--------------------------|
| Best-fit   | 0.0039(+11, -7) | 0.00096(11) | 1.120(7) | 223.8(14) | 0.133(3) | 2848.06(13) | 61.5(1.8) | 19.70(15) | 1390.49 | 1151.00 | 239.50 |
| Early caustic | 0.0070 | 0.00104 | 1.121 | 218.9 | 0.140 | 2847.90 | 58.5 | 19.68 | 1601.44 | 1229.47 | 371.98 |
| Best nonplanet | 0.0300 | 0.00088 | 1.090 | 187.9 | 0.144 | 2846.20 | 57.5 | 19.68 | 1601.44 | 1229.47 | 371.98 |
| Single-lens | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |

Note. — The units for $t_0$ are HJD $- 2,450,000$. 

![Figure 1](image.png)

**Fig. 1.**—Light curve with best-fitting and single-lens models of O235/M53. The OGLE and MOA measurements are shown as red filled circles and open blue circles, respectively. The top panel presents the complete data set during 2003 (main panel) and the 2001–2003 OGLE data (inset). For clarity, the error bars were not plotted, but the median errors in the OGLE and MOA points are indicated in the legend. The bottom panel is the same as the top panel, but with the MOA data grouped in 1 day bins, except for the caustic crossing nights, and with the inset showing MOA photometry during 2000–2003. The binary- and single-lens fits are plotted in flux units normalized to the unlensed source star brightness of the best planetary fit, and they are indicated by the solid black and cyan dashed curves, respectively.
$q < 0.03$ for a planetary microlensing event, and so O235/M53 is clearly in the planetary event category.

We have carried out a systematic search in parameter space to try to find sets of model parameters that might explain the observed light curve with a larger mass ratio. Binary microlensing models with $q \geq 0.1$ that traverse a caustic curve in ~7 days have much larger magnifications inside the caustic curve than is observed for O235/M53. These binary-lens events also have much larger deviations from a single-lens light curve before and after the caustic crossings. As the mass ratio is decreased, the best-fit light curves approach the observed light curves, with much weaker caustic crossing deviations. In Figure 2, we show a close-up of the 7 day deviation with the best-fit planetary model, compared with the best nonplanetary model with $q \geq 0.03$ and best-fit single-lens model. The nonplanetary binary models and single-lens models are strongly disfavored with fit $\chi^2$-values that are larger by $\Delta \chi^2 = 210.96$ and $\Delta \chi^2 = 650.96$, respectively. In both cases, the $\chi^2$ improvement for the best-fit model is quite significant in both the MOA and OGLE data sets (see Table 1). The failure of the nonplanetary binary model can be seen in the Figure 2 insets. This model predicts both stronger caustic signals and significant crossing deviations. In Figure 2, we show a close-up of the 7 day approach the observed light curves, with much weaker caustic crossings. As the mass ratio is decreased, the best-fit light curves approach the observed light curves, with much weaker caustic crossing deviations. In Figure 2, we show a close-up of the 7 day deviation with the best-fit planetary model, compared with the best nonplanetary model with $q \geq 0.03$ and best-fit single-lens model. The nonplanetary binary models and single-lens models are strongly disfavored with fit $\chi^2$-values that are larger by $\Delta \chi^2 = 210.96$ and $\Delta \chi^2 = 650.96$, respectively. In both cases, the $\chi^2$ improvement for the best-fit model is quite significant in both the MOA and OGLE data sets (see Table 1). The failure of the nonplanetary binary model can be seen in the Figure 2 insets. This model predicts both stronger caustic signals and significant deviations 13–20 days after the second caustic crossing that are not consistent with the observations. This model also shows some discrepancies at magnifications of less than 2, but these are not as strongly excluded because of the higher photometric uncertainties at lower magnification.

Also shown in Figure 2 is a planetary model with an earlier caustic crossing and a larger planet mass ratio: $q = 0.0070$. This fit represents a distinct local minimum of the $\chi^2$ surface and is disfavored by only $\Delta \chi^2 = 7.37$ or ~2.7 $\sigma$. This is not accounted for by our 1 $\sigma$ uncertainty on $q = 0.0039$. Therefore, we have increased the upper error estimate on the planetary mass ratio to 0.0011, so that the actual uncertainty in $q$ will be bounded by our error estimates at the 3 $\sigma$ level. In Table 1, we also list the parameters for these alternative models.

Finally, the first OGLE observation after the second caustic crossing indicates a magnification below all of the binary models shown by about 3.6 $\sigma$. Such an outlier is not unusual because the real photometric error distributions for crowded field photometry generally have larger wings than a Gaussian distribution. Three of the 183 OGLE measurements are outliers from the best fit by more than 3 $\sigma$, and 16 are outliers by more than 2 $\sigma$. These outlier points do not appear to cluster in the vicinity of the planetary deviation. If this single data point did indicate a real light-curve deviation, it could be explained by a small variation in the planetary microlensing model, such as a moon orbiting the planet, but there is no nonplanetary model that could help to explain it.

4. FURTHER CONSTRAINTS ON THE SOURCE AND LENS

Most microlensing events have only a single measurable parameter, $r_E$, that constrains the lens mass, distance, and transverse velocity with respect to the line of sight to the source. However, time-resolved observations of binary event caustic crossings resolve the finite source star effects and partly remove these degeneracies (Alcock et al. 2000; Witt & Mao 1994; Nemiroff & Wickramasinghe 1994; Gould 1994) by allowing a measurement of the Einstein angular radius given by $\theta_E^2 = (4GM_{\text{lens}}/c^2)(D_{\text{source}} - D_{\text{lens}})/(D_{\text{lens}}D_{\text{source}})$.

Using the flux parameters of the microlensing fit, we obtained $I = 19.70 \pm 0.15$ for the source star and $I = 20.7 \pm 0.4$ for the blended component. This source star magnitude, plus the $V-I$ color from § 2, can be compared with the bulge color-magnitude diagram of Holtzman et al. (1998), and this indicates that the source is probably a bulge star near the main-sequence turnoff. To determine the angular radius of the source star, we used the color-color relations of Bessell & Brett (1988) together with empirical relations between $V-K$ and surface brightness derived from interferometry observations of nearby main-sequence stars (van Belle 1999; di Benedetto 1998).

We find $\theta_E = 0.50 \pm 0.05$ $\mu$as, which, combined with our measurement of $\rho$, yields $\theta_E^2 = 520 \pm 80$ $\mu$as. This yields the following relation between the lens mass and distance:

$$\frac{M_{\text{lens}}}{M_\odot} = 0.123 \left( \frac{\theta_E}{\text{mas}} \right)^2 \frac{D_{\text{source}}}{\text{kpc}} \frac{x}{1 - x},$$

where $x = D_{\text{lens}}/D_{\text{source}}$. If we combine this relation with the mass-luminosity relations of Kroupa & Tout (1997) for main-sequence stars, and if we require that the lens luminosity at a given distance does not exceed the blend flux, we obtain an upper limit (with 90% confidence) of $D_{\text{lens}} < 5.4$ kpc. Thus, if the lens is a main-sequence star, it must be in the Galactic disk.

In Figure 3, we show equation (1) together with the results of a maximum likelihood analysis based on our measurements of the Einstein ring and its characteristic crossing time. The likelihood function was calculated using the Galactic disk models of Han & Gould (1996). We then obtain (with 90% confidence) $D_{\text{lens}} = 5.2^{+2.9}_{-2.0}$ kpc, from which we infer the lensing system to comprise an M2–M7 dwarf star of mass 0.36^{+0.03}_{-0.03} M_\odot with a giant planetary companion of 1.5^{+0.1}_{-0.2} M_J (Jupiter masses). The planet is in a wide orbit with a transverse separation of 3.0^{+1.1}_{-0.3} AU.

Another possibility for the lens is that it could be a remnant object such as a white dwarf, neutron star, or black hole. If the
The situation in the case of O235/M53 was helped by the measurement of finite source effects. If the lens is a main-sequence star, then, as shown in the previous section, it must be an M dwarf with an \( \sim 1.5 M_J \) planetary companion.12 There is a nonnegligible chance that the lens is a white dwarf, and a much smaller chance that it is a neutron star, but in both cases, a planetary companion below the nominal 13.6M\(_J\) threshold is required. Only in the unlikely case of a massive black hole primary could the secondary be outside the range traditionally associated with a planet.

There are some prospects for follow-up observations of this event. Our measurements of the finite source effects imply a proper motion of the lens with respect to the source of \( \mu = \theta_\text{E}/H_\text{E} = 3.1 \pm 0.4 \text{ mas yr}^{-1} \). High-resolution imaging carried out \( \sim 10 \) years from now with the James Webb Space Telescope or with adaptive optics systems should be able to resolve the lens and source stars, providing direct measurements (Han & Chang 2003; Alcock et al. 2001) of the color and brightness of the lens as well as confirmation of the proper-motion measurement.

We present these observations as a demonstration of the planetary microlensing phenomenon. The power of microlensing is in its ability to acquire statistics on many systems (Bennett & Rhie 2002). These include planets in wide orbits, very low mass planets, and even planets in other galaxies (Covone et al. 2000; Bond et al. 2002). The challenge now for the microlensing community is to develop effective strategies for finding more planetary microlensing events.13

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12 The only other M dwarf star known to have planetary companions is Gliese 876 (Marcy et al. 2001).

13 Numerical photometry of OGLE 2003-BLG-235/MOA 2003-BLG-53 is available from the Web sites for OGLE http://ogle.astrouw.edu.pl and MOA http://www.physics.auckland.ac.nz/moa.

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