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THE OPTICAL GRAVITATIONAL LENSING EXPERIMENT: THE DISCOVERY OF THREE FURTHER MICROLENSING EVENTS IN THE DIRECTION OF THE GALACTIC BULGE[1]

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ABSTRACT

Three newly discovered microlensing events in the direction of the Galactic bulge are presented, increasing to four the total number of events detected by the OGLE collaboration. The timescales and magnifications of the events range from 10 to 45 days and from 1.26 to 6.5, respectively. The locations of the lensed objects in the color-magnitude diagram indicate that one is a red giant and three are main-sequence stars. All observed features suggest microlensing as the only plausible explanation of the observed light variations.

Subject headings: dark matter — gravitational lensing — stars: low-mass, brown dwarfs

1. INTRODUCTION

The Optical Gravitational Lensing Experiment (OGLE) is a long-term observational program with the main goal of searching for dark, unseen matter using microlensing phenomena. The idea of employing microlensing for that purpose was originally proposed by Paczyński (1986, 1991) and then by Griest (1991) and Griest et al. (1991). The Magellanic Clouds and the Galactic bulge are the most natural locations for conducting such a search, owing to a large number of background stars that are potential targets for microlensing. The LMC and SMC stars may be lensed mostly by the Galactic halo objects; in the case of the Galactic bulge stars, one expects an additional component—microlensing by low-mass disk stars. In both cases the optical depth for microlensing is very small—about 10^{-6}. Therefore, a massive, long-term survey must be conducted to (*a*) detect and (*b*) collect a statistically significant sample of microlensing events, to draw any conclusion about the nature of dark matter.

The light curve of a microlensing event has three very characteristic features which distinguish it from other types of variability: (*a*) the light curve is symmetric around the brightness maximum, and it has a characteristic shape (Paczyński 1991); (*b*) as long as the lensing object is much fainter than the lensed star, the light curve should be achromatic because the event is color-independent; and finally (*c*) the light brightening should not repeat, because the probability that the same star has been lensed twice is practically zero. The timescale of the event is a function of the mass of the lensing object, its transverse velocity, and its geometry, i.e., distances to the lensing and lensed objects (Paczyński 1991).

The OGLE project started in 1992 (Udalski et al. 1992), and the Galactic bulge has been selected as the first target. After two observing seasons, the first microlensing event toward the Galactic bulge has been discovered (Udalski et al. 1993a). Two other teams conduct similar searches in the direction of the LMC, and both have reported the detection of microlensing event candidates: the MACHO collaboration (Alcock et al. 1993) and the EROS collaboration (Aubourg et al. 1993).

In this *Letter* we report the discovery of three further microlensing events after analyzing about 75% of the collected data. These recent discoveries increase our sample to four events. We present evidence supporting microlensing as the only reasonable explanation of the observed light variations. However, we do not attempt here any statistical analysis of the events, as this will be the scope of a forthcoming paper in which all observing material will be carefully analyzed.

2. OBSERVATIONS AND REDUCTIONS

About 2000 frames of the Galactic bulge were collected in the 1992 and 1993 observing seasons with 1 m Swope telescope at Las Campanas Observatory, Chile, which is operated by the Carnegie Institution of Washington. A single-chip CCD camera with a 2048 × 2048 pixel Ford/Loral detector with the scale of 0".44 pixel^{-1} was used throughout all observations. A total of 150 nights have been allocated in 1992 and 1993 for the OGLE project. The details of hardware and data pipeline, the coordinates of observed fields, the number of observed stars per field, and the error analysis, as well as the log of the 1992 and 1993 observations, can be found in Udalski et al. (1992) and Udalski et al. (1994).

The collected frames were reduced almost in real time using the procedure described in detail in Udalski et al. (1992). For easy manipulation of the huge amount of data the databases have been built for each field and color (Szymański & Udalski 1993). To select the potential microlensing event candidates, the following procedure has been applied. All observations constitute two distinct sets of observations due to the 8 month gap between them. Therefore, we have treated them as two separate runs. Thirteen fields were observed in both seasons. First, from all 1992 season observations we extracted about 1.1×10^6 stars which fulfilled nonvariability criteria (Udalski

[1] Based on observations obtained at the Las Campanas Observatory of the Carnegie Institution of Washington.

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TABLE 1

MICROLENSED STARS

Parameter	OGLE #1	OGLE #2	OGLE #3	OGLE #4
Lensed Star RA_{2000}	$18^h04^m24^s.82$	$18^h02^m52^s.08$	$18^h04^m43^s.41$	$18^h04^m16^s.27$
Lensed Star DEC_{2000}	$-30°05'58''.8$	$-30°04'21''.5$	$-30°14'09''.0$	$-29°51'56''.7$
Comparison A RA_{2000}	$18^h04^m23^s.58$	$18^h02^m51^s.42$	$18^h04^m44^s.11$	$18^h04^m15^s.58$
Comparison A DEC_{2000}	$-30°05'47''.0$	$-30°04'17''.6$	$-30°14'05''.9$	$-29°52'00''.3$
Comparison A V	$16^m.907$	$16^m.380$	$17^m.182$	$18^m.433$
Comparison A $V-I$	$2^m.213$	$1^m.773$	$1^m.974$	$2^m.093$
Comparison B RA_{2000}	$18^h04^m25^s.79$	$18^h02^m50^s.88$	$18^h04^m44^s.16$	$18^h04^m16^s.00$
Comparison B DEC_{2000}	$-30°06'13''.0$	$-30°04'21''.1$	$-30°14'14''.4$	$-29°52'07''.5$
Comparison B V	$17^m.148$	$15^m.994$	$17^m.042$	$17^m.591$
Comparison B $V-I$	$1^m.919$	$1^m.012$	$2^m.222$	$1^m.899$

et al. 1993a). Then all observations collected in 1993 were compared with the mean 1992 value, and if more than four observations of a given object deviated by more than 3 σ from the 1992 mean value, the object was marked as suspected. A variety of filters were then applied to the selected sample of suspected objects, leaving a small number of objects which increased in brightness and did not vary randomly. In this way the first microlensing event candidate has been selected (Udalski et al. 1993a).

The procedure can be reversed, i.e., the 1993 observations can be used for establishing the "nonvariable" star database for the search for microlensing events in the 1992 data. A similar number of nonvariable stars has been extracted from the 1993 data. The suspected objects were selected using analogous criteria and passed through the same filters. Three further microlensing events were detected after approximately 50% of the 1992 data set had been analyzed.

The final photometry of each event was derived by running the DOPHOT reduction photometry program (Schechter, Mateo, & Saha 1993) in the fixed-position mode on 150 × 150 pixel subframes centered on the microlensed object. The differential magnitudes were derived with respect to magnitudes of two nearby bright comparison stars which were constant over the entire observing season. We did this for two reasons. First, we wished to minimize errors introduced by the variable point-spread function (PSF). PSF variations were significantly removed by the "frame dividing method" of reduction (Udalski et al. 1992); nevertheless, some microlensed stars fell on the subframe edge and were relatively more sensitive to the PSF inconsistency. Moreover, one star was located in the overlap area of two fields. In this case, differential photometry was the only way to avoid systematic errors. Second, we found that in the fixed-position mode used in our reductions, when the brightness in the I-band on the template frame (the good seeing frame from which the position of the star is determined for further reductions) is below 18 mag, it may happen that the position derived for such a faint object is not precise enough. When the star brightens by more than 1 mag, even a small error in its position (it is kept constant for all subsequent frames) can lead to a relatively large error in magnitude. This effect is negligible for amplitudes smaller than 1 mag and for stars brighter than $I = 18$ mag. The good seeing frame close to the maximum brightness of the event was selected as the template in the final reductions to get rid of this effect.

3. NEW MICROLENSING EVENTS

Table 1 lists all four microlensing events discovered so far in the direction of the Galactic bulge by the OGLE collaboration. For each event we give J2000.0 coordinates of the lensed star as well as magnitudes and positions of the two comparison stars. Table 2 lists the parameters of the four-parameter fit to the theoretical light curve. Figure 1 (Plate L7) shows for each object a 30″ × 30″ I-band subframe at the normal brightness and near-maximum of the microlensing event. This figure can serve as a finding chart. Figures 2, 3, and 4 show light curves of the newly discovered events. They are briefly characterized below.

3.1. *OGLE Lens 2*

The OGLE microlensed star 2 is located in the overlapping area of the BW5 and BWC fields of Baade's window (BW5 I 178651/BWC I 10648). Therefore, the number of independent observations almost doubled, giving the best coverage of the light curve out of all other microlensing events. The timescale as well as the amplitude (2.0 mag) are the largest in the entire sample. A few observations in the V-band during the event show that the light curve is achromatic within the errors of measurement. At normal brightness the V-band measurements are close to the detection limit. Nevertheless, one can locate the microlensed star on the color-magnitude diagram (Udalski et al. 1993b) as a typical star near the Galactic bulge main-sequence turnoff point ($V = 20.7$, $V-I = 1.6$). The long duration of the event suggests that the lensing object is relatively massive. If so, it might be noticeable in the IR part of the spectrum of the star. When it separates in a few years by a few hundredths of an arcsecond due to its proper motion, it could also be detected from space by the *Hubble Space Telescope*.

3.2. *OGLE Lens 3*

The Baade's window BW3 field star designated BW3 I 161225 is the brightest object lensed until now. Therefore, its photometry is very precise, and this relatively small-amplitude event was easily detected. V-band measurements show that the $V-I$ color of the object was constant during the event with high accuracy, which means that the event was achromatic. The lensed star ($V = 17.63$, $V-I = 1.74$) is located in the Galactic bulge giant branch close to the "red clump" (Udalski et al. 1993b). The duration of the event is the shortest observed so far, with the timescale equal to 10.7 days.

TABLE 2

BEST FOUR-PARAMETER FIT OF THE THEORETICAL LIGHT CURVE

Parameter	OGLE #1	OGLE #2	OGLE #3	OGLE #4
Moment of maximum T_0	$1153^d.9 \pm 1.0$	$803^d.4 \pm 0.3$	$831^d.5 \pm 0.5$	$807^d.3 \pm 0.1$
Time scale t_0	$25^d.9 \pm 1.7$	$45^d.0 \pm 0.9$	$10^d.7 \pm 0.7$	$14^d.0 \pm 0.8$
Magnification A	2.7 ± 0.3	6.5 ± 0.9	1.26 ± 0.02	5.8 ± 1.0
I magnitude	$18^m.82 \pm 0.02$	$19^m.05 \pm 0.02$	$15^m.89 \pm 0.01$	$19^m.27 \pm 0.02$

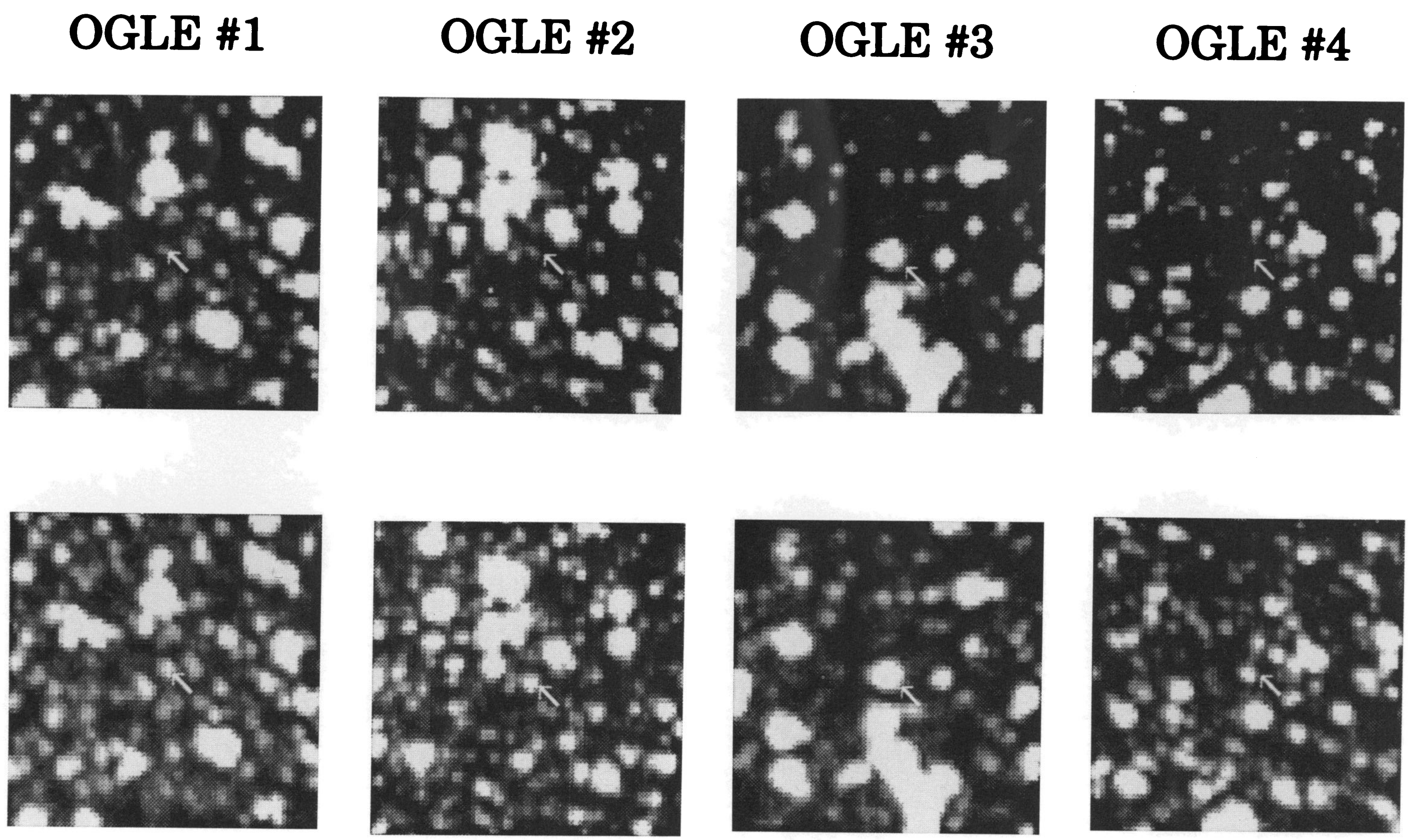

FIG. 1.—*I*-band 30″ × 30″ images centered on the microlensed stars. The upper frame shows the microlensed star (*white arrow*) at the normal brightness; the lower one, close to the moment of maximum magnification. North is up, and east is to the left.

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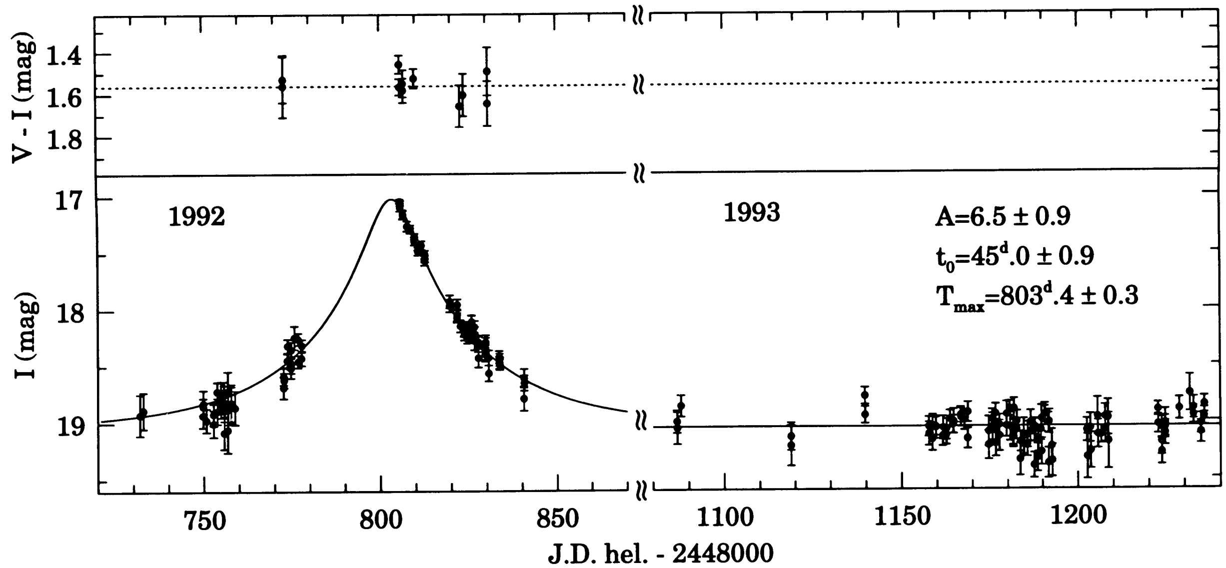

FIG. 2.—Light and color curves of OGLE microlensing event 2 (BW5 I 178651/BWC I 10648). The solid line represents the best fit of the theoretical microlensing light curve. Error bars correspond to the formal error returned by the DOPHOT photometry program rescaled by 1.3 to approximate the observed errors.

3.3. *OGLE Lens 4*

OGLE microlensing event 4 (BW4 I 111538) is characterized by a large magnification and a short timescale. Unfortunately, the event is not very well covered by the observations, in particular on its rising branch. Nevertheless, the theoretical light curve fits all observations well. However, the duration of the event may have fairly large error. Normal brightness of the star in the V-band is at the detection limit, and it can be measured only on the best-seeing, dark frames. Within errors, the $V-I$ colors at maximum and minimum light are the same, i.e., the light curve is achromatic. The location on the color-magnitude diagram ($V = 20.8$, $V-I = 1.5$) is similar to those of OGLE events 2 and 1 (Udalski et al. 1993a), i.e., near the turnoff point of the Galactic bulge main sequence.

4. CONCLUSIONS

Three new microlensing events have been found in the OGLE data, bringing their total number to four. All events fit well the theoretical light curve expected for classical microlensing. In three cases where V-band observations are precise enough, the light curve is achromatic as well. Also, for at least one observing season the brightness of the lensed stars remained at a constant level, suggesting nonrepeatability of the events, although only observations in the coming years will confirm whether the brightening of each object was unique.

The colors of the lensed stars and the distribution of event parameters also strongly suggest that we may have indeed detected true microlensing events. First, the location on the color-magnitude diagram shows that the lensed stars are such distinct objects as a red giant and main-sequence stars. It is difficult to imagine a single physical process that could produce identical sorts of light curves in stars with such different properties. Second, only microlensing provides a natural explanation why we observe the same light-curve shape, but with different durations and magnifications. Third, we have not found, nor do we know of, any sort of intrinsic stellar

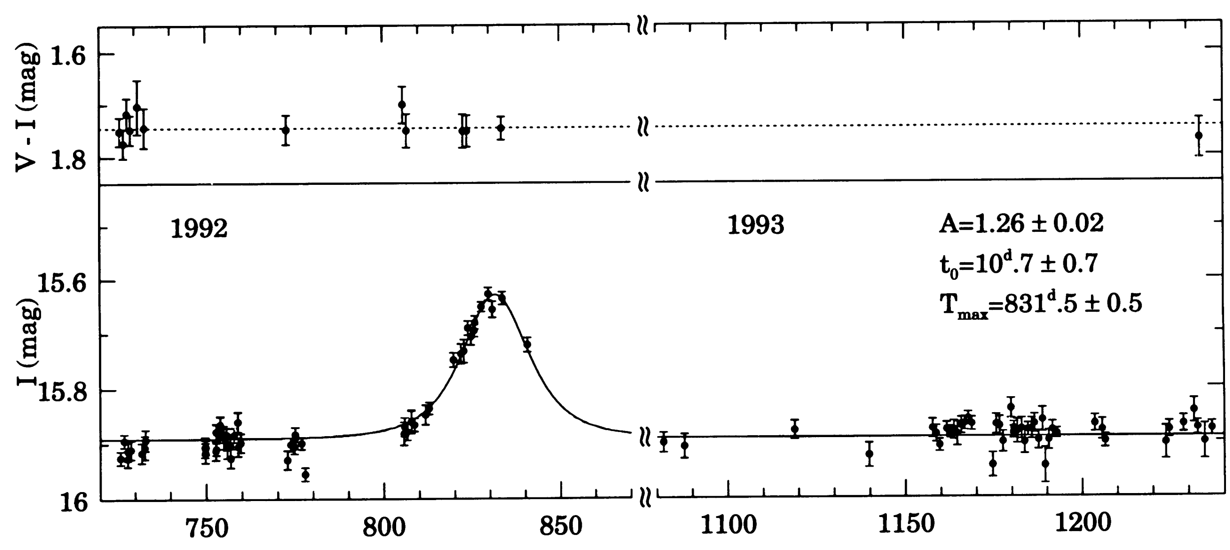

FIG. 3.—Same as Fig. 2, but for OGLE microlensing event 3 (BW3 I 161225)

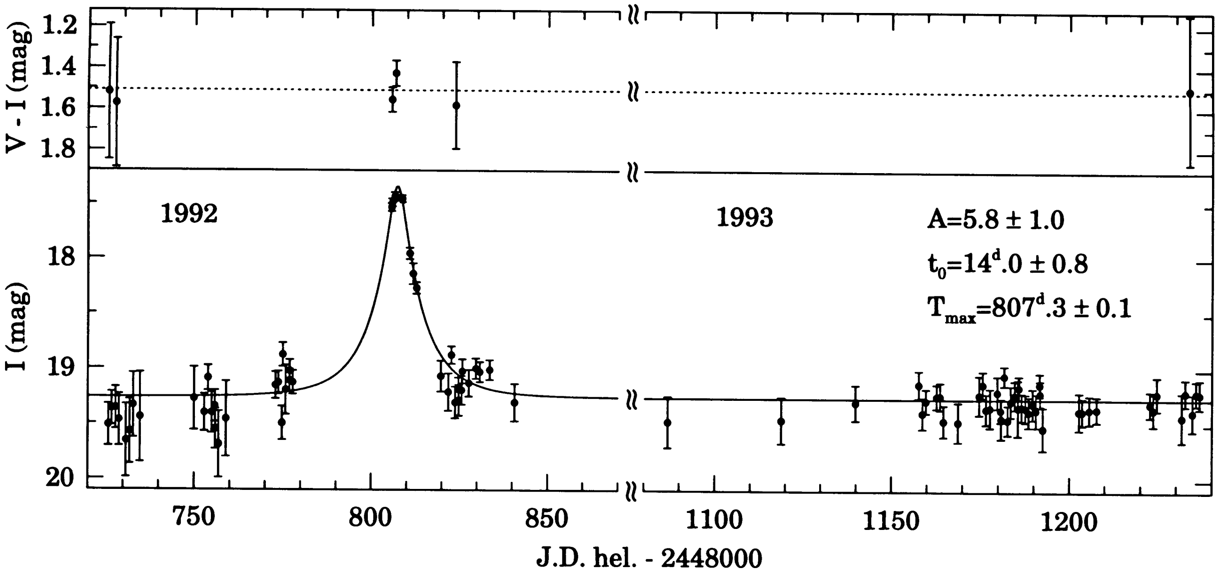

FIG. 4.—Same as Fig. 2, but for OGLE microlensing event 4 (BW4 I 111538)

variability which even remotely resembles the variability expected from microlensing. We conclude that all of the observed properties of our four events in our sample are consistent with microlensing.

It should be stressed, however, that the events presented in this *Letter*, as well as OGLE event 1, represent the most prominent cases where there is no doubt of the nature of light variability. Thus this sample cannot be considered as statistically representative. A few more candidates with smaller signal-to-noise ratio have already been found, and full statistical analysis of the frequency of microlensing events in the direction of the Galactic bulge, taking into account all possible selection effects, will be presented in the forthcoming paper.

Photometry of the OGLE microlensing events, as well as a regularly updated OGLE status report, can be found over the Internet network from "sirius.astrouw.edu.pl" host (148.81.8.1), using the "anonymous ftp" service (directory/ogle, files README, lens*.res, ogle.status). The report contains the latest news and references to all OGLE-related papers, and eventually the PostScript version of some publications.

The OGLE data (FITS images including frames with OGLE events 2–4) are accessible for astronomical community from the NASA NSS Data Center. Send e-mail to archives@nssdc.gsfc.nasa.gov with the subject line REQUEST OGLE ALL, and put requested frame numbers (in the form MR00NNNN, where NNNN stands for frame number according to OGLE notation [Udalski et al. 1992]), one per line, in the body of the message. Requested frames will be available using "anonymous ftp" service from nssdc.gsfc.nasa.gov host in the location shown in the return e-mail message from archives@nssdc.gsfc.nasa.gov.

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Note added in proof.—After this *Letter* had been accepted for publication, the fifth and sixth microlensing events were detected in the OGLE data. Their parameters are as follows for OGLE event 5 (BWC I 120698) and OGLE event 6 (MM5-B I 128727), respectively: timescale: 11.5 ± 0.4 and 8.4 ± 0.3 days; magnification, 11.5 ± 2.5 and 6.9 ± 2.5; moment of maximum, JD 2,448,824.33 $\pm$ 0.04 and JD 2,448,818.90 $\pm$ 0.15; *I* magnitude: 17.88 ± 0.02 and 18.07 ± 0.01. The photometry and finding chart of OGLE events 5 and 6 can be obtained over the Internet network via anonymous ftp service from the sirius.astrouw.edu.pl (148.81.8.1) host (directory/ogle) or via "World Wide Web" WWW: "http://www.astrouw.edu.pl/".