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THE OPTICAL GRAVITATIONAL LENSING EXPERIMENT: OGLE NO. 7: BINARY MICROLENS OR A NEW UNUSUAL VARIABLE?[1]

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ABSTRACT

We present the light curve of an unusual variable object, OGLE No. 7, detected during the OGLE search for microlensing events. After one season of being in a low, normal state, the star brightened by more than 2 mag with a characteristic double-maximum shape, and returned to normal brightness after 60 days. We consider possible explanations of the photometric behavior of OGLE No. 7. The binary microlens model seems to be the most likely explanation—it reproduces well the observed light curve and explains the observed colors of OGLE No. 7. The characteristic timescale of the OGLE No. 7 event, t_E, is equal to 80 days, the longest observed to date. The binary microlens model predicts that the spectrum of the star should be composite, with roughly 50% of its light in the I-band coming from a nonlensed source.

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

1. INTRODUCTION

The Optical Gravitational Lensing Experiment (OGLE) is a long-term observing project with the main goal of searching for dark matter in our Galaxy using microlensing (Paczyński 1986). After 2 years of continuous monitoring of approximately two million nonvariable stars in the direction of the Galactic bulge, 10 events have been detected (Udalski et al. 1993a, Udalski et al. 1994a, c). The inferred optical depth of microlensing $(3.3 \pm 1.2) \times 10^6$ is higher than previous theoretical estimates (Udalski et al. 1994c).

A microlensing event caused by a single, pointlike lens is not repeatable and has an achromatic light curve with a well-defined, characteristic shape which is symmetric around the maximum of brightness (Paczyński 1986, 1991). All the OGLE microlensing events except OGLE No. 7 displayed such photometric behaviors (but see Mao & Di Stefano 1995 for a slightly better binary fit for OGLE No. 6). All the reported MACHO (Alcock et al. 1994) and EROS (Aubourg et al. 1993) events can also be well fitted by single lenses. However, it is well known that majority of stars are found in binary or multiple systems (Abt 1983). Therefore it is natural to expect some microlensing events to be caused by binary systems. The light curve of such events might be considerably different from that of single microlens events and would depend on the geometry of lensing (Mao & Pacyński 1991; Mao & Di Stefano 1995).

One of the OGLE microlensing candidates found during the OGLE search, OGLE No. 7, exhibits very unusual light variations which do not resemble variations of any known variable stars. On the other hand, the light variations are strikingly similar to the theoretical light curves possible for binary microlenses (Mao & Paczyński 1991). In this *Letter* we present a detailed analysis of the variability of the OGLE No. 7 candidate, emphasizing binary microlensing as a possible explanation of the observed light variations.

2. OBSERVATIONS

The OGLE microlensing search is conducted using the 1 m Swope telescope at Las Campanas Observatory which is operated by the Carnegie Institution of Washington. Collected CCD frames feed the data pipeline which, almost in real time, derives the photometry of objects. Details of the reduction techniques are described in Udalski et al. (1992).

An OGLE No. 7 candidate, the Baade's Window field BW8 (Udalski et al. 1992) star I 198503, has been detected during the regular microlensing search as described in Udalski et al. (1993a) and Udalski et al. (1994a). To minimize the photometric errors resulting from instrumental errors and from the general technique of reductions used in the OGLE search, the final differential photometry of OGLE No. 7 with respect to two bright, nearby stars was derived as in Udalski et al. (1994a). Differential photometry was then tied to the standard system. Table 1 contains the position and colors of OGLE No. 7 and the comparison stars. A 45″ × 45″ region centered on the star is shown in Figure 1 (Plate L3).

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

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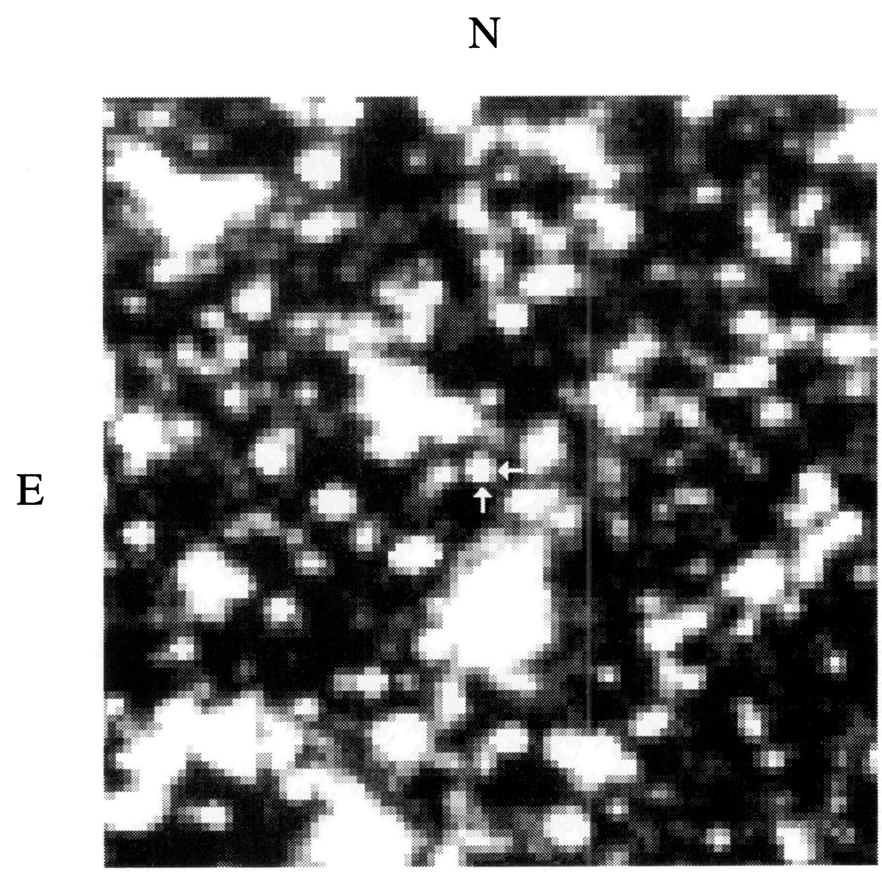

FIG. 1.—45″ × 45″ *I*-band images centered on the OGLE No. 7 star. Two arrows identify the lensed star. North is up and east is to the left.

UDALSKI et al. (see 436, L103)

TABLE 1

OGLE No. 7 AND COMPARISON STARS

Parameter	OGLE No. 7	Comparison A	Comparison B
R.A.$_{2000}$	$18^h03^m35^s.74$	$18^h03^m34^s.58$	$18^h03^m37^s.18$
Decl.$_{2000}$	$-29°42'01''.3$	$-29°42'08''.6$	$-29°41'57''.6$
V	$19^m.4$	$17^m.45$	$17^m.57$
$V-I$	$1^m.9$	$2^m.11$	$2^m.12$

3. LIGHT CURVE OF OGLE NO. 7

Figure 2 shows the light and $V-I$ color curves of OGLE No. 7 from the 1992 and 1993 observing seasons. During the 1992 observing season the brightness of OGLE No. 7 remained at a constant level with $I \approx 17.5$ mag and the star therefore was included in the nonvariable object database for the microlensing search. Dramatic light changes occurred in the next (1993) observing season. At the beginning of the 1993 observing season the star was still close to its previous low light level: $I \approx 17.3$. Then it brightened gradually by about 0.2 mag. Around day JD $-2{,}448{,}000 = 1140$ it rose rapidly by about 2 mag reaching $I \approx 15.1$. Unfortunately, due to telescope scheduling constraints and unusually bad weather, that part of the light curve is sparsely covered by observations. Moreover the observation taken at the maximum light was obtained in poor seeing conditions. Nevertheless, due to the large brightness of OGLE No. 7 at that time, the derived photometry is reliable. After reaching the maximum, the brightness of OGLE No. 7 faded and reached a plateau about 1 mag brighter than the minimum level. Then it began to rise again, followed by an abrupt drop to the level 0.3 mag over the minimum level. After that, OGLE No. 7 gradually faded to the minimum brightness. The overall light variations have a double-maximum structure with U-shape changes between them. OGLE No. 7 was observed mainly in the I filter. From six V-band observations the $V-I$ color of the star is $V-I = 1.94 \pm 0.07$. There is no color information during the event. However, one observation taken after the event when the star was still about 0.3 mag above the minimum suggests no significant color variation.

The OGLE No. 7 candidate is being continuously monitored during the OGLE 1994 observing season. At the time of this writing, the brightness of the star has remained at the low level with $I \approx 17.5$ mag over the entire period JD $-2{,}448{,}000$: 1439 – 1602.

4. WHAT IS OGLE NO. 7?

The photometric light curve of the OGLE No. 7 indicates that we have discovered a very mysterious object with unusual properties. In this section we explore its true nature.

4.1. *An Eruptive Variable?*

The rapid increase of brightness might suggest some kind of eruptive variable. The amplitude of brightening excludes any type of catalysmic variables (CVs) other than dwarf novae (DN) or low-mass X-ray binaries (LMXBs). However, it seems unlikely that OGLE No. 7 is a DN or LMXB. First, the light curve does not resemble that of DN or LMXB, and the duration of the event is much longer than typical DN outbursts or superoutbursts. The light curve is very smooth, which indicates no light changes larger than a few hundredths of a magnitude whereas CVs usually exhibit significant variations caused by reflection effects and/or by flickering. Second, the $V-I$ color of OGLE No. (Table 1), $V-I = 1.9$, seems to be too red for a typical DN or LMXB system, even after taking into account extinction toward the bulge (upper limit: $E_{V-I} = 0.55$ mag; Paczyński et al. 1994). Moreover, we are not aware of any detection of an X-ray source when OGLE No. 7 was in a high state, nor of any known X-ray source close to the position of OGLE No. 7.

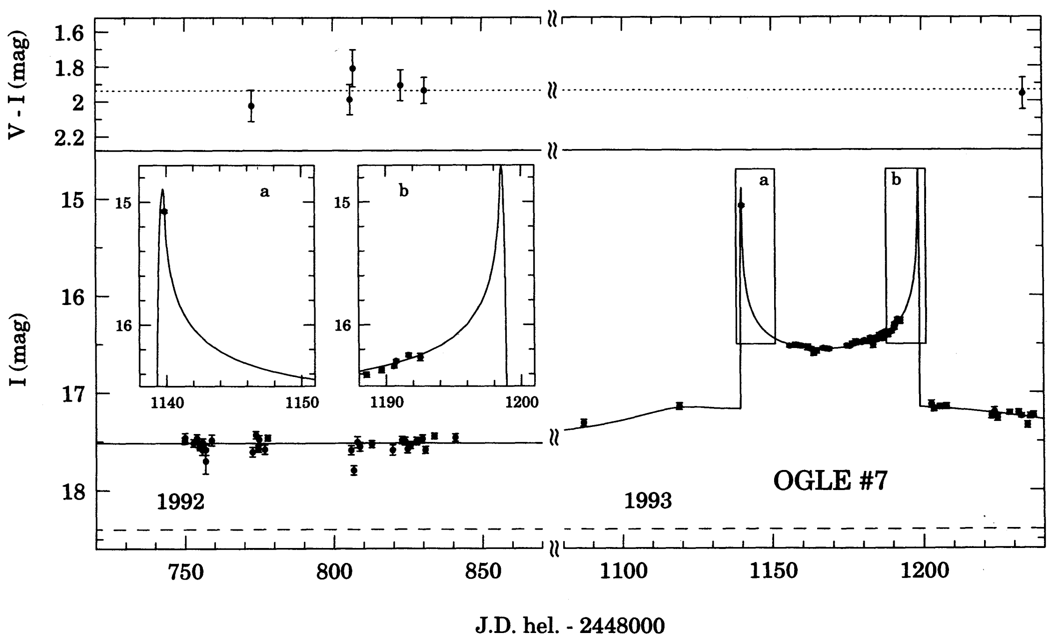

FIG. 2.—Light and $V-I$ color curves of the OGLE No. 7. The error bars correspond to the formal errors returned by the DoPhot photometry program (Schechter, Mateo, & Saha 1993) rescaled by 1.4 to approximate errors of observations (Udalski et al. 1994c). The solid line shows the light curve of the best binary microlens model. Two blow-ups (a, b) show details of the light curve around the two peaks in the model light curve. Although the model parameters (eq. [1]) are found using a point source approximation, the light curve shown here is obtained by convolving the point source light curve with that of a star with radius $R_* = 5$ $R_\odot$ and a "cosine" limb darkening profile in the I band. We adopt a transverse velocity of 200 km s^{-1}. The dashed line indicates the magnitude of the extra light provided by the binary lens and/or an unresolved nearby source.

Another possibility could be a flaring late spectral type star. However, typical flares in such stars last minutes or hours, and we do not know any object with flares lasting for several days. With such long duration coverage of OGLE No. 7 we would expect at least some traces of another flaring activity but we have not registered any additional light increase.

The optical spectrum of OGLE No. 7 could shed some light on the nature of the object. As CVs and flaring stars often reveal emission lines, their presence would be an argument in favor of an eruptive nature for the object. Also, if the observed brightening is due to some eruptive processes, it should repeat in the future.

4.2. *A Binary Lens?*

Lensing by binaries is naturally expected in ~10% of the OGLE events (Mao & Paczyński 1991). It is thus statistically plausible to have one binary lensing event in the 10 OGLE events sample (Udalski et al. 1994c). Furthermore, the characteristic U-shape light variations between maxima in OGLE No. 7's high state can be found in the theoretical light curves of binary lenses (e.g., Mao & Paczyński 1991). The U shape is a result of the source crossing the caustics. Another important argument in favor of the binary lens interpretation is provided by the colors of OGLE No. 7, which indicate that the star is a typical Galactic bulge main-sequence turnoff point star (Udalski et al. 1994c) and thus can be a source for microlensing.

The fitting of a binary light curve has been studied by Mao & Di Stefano (1995), in which the technical details can be found. The fitting involves the search for a global minimum of a χ^2 measure in a multiple dimensional parameter space. For the minimal binary model, there are seven parameters: the total mass of the binary, M; the mass ratio of the individual masses, $q = m_2/m_1$; their separation, a, as projected onto the lens plane (defined in terms of the center of mass of the binary); the closest approach to the center of mass, b; the time of closest approach, t_b; the angle between the axis of the binary and the trajectory, θ; and, the magnitude of the star at the minimum light, I_0. For the Galactic bulge observations, we need one more parameter, f, the light contributed by the lensed star at minimum light. This parameter is needed to take into account the light contribution of the lens(es) and/or a nearby star located close to the source with separation smaller than the seeing disk ($\lesssim 1''$).

In Figure 2 we plot our best-fit model. The model has a χ^2 (as defined in Mao & Di Stefano 1995) of 139 for 83 data points (75 degree of freedom). The χ^2 for the varying part (between days JD $-2{,}448{,}000$: 1085 − 1240) of the light curve is 57 for 51 data points. The best-fit parameters are,

$$q = 1.02\ ; \quad a = 1.14R_{\rm E}\ ; \quad b = 0.050R_{\rm E}\ ; \quad \theta = 48^\circ\!.3\ ;$$
$$t_{\rm E} = 80 \text{ day}\ ; \quad t_b = 1172.5 \text{ day}\ ; \quad f = 56\%\ ; \quad I_0 = 18.1\ , \tag{1}$$

where $R_{\rm E}$ is the Einstein radius projected onto the source plane for the total mass M. The lensing geometry is shown in Figure 3. We have assumed that the lensed star is a point object, and ignored the circular motions of the lenses and the Earth, which are on the scale of a few AU.

The best fit indicates that about half of the OGLE No. 7 light in the normal state must come from an additional source. There are two obvious possibilities for the additional light: a very close optical companion of the lensed star which cannot be separated from the ground, or, the binary lensing system itself.

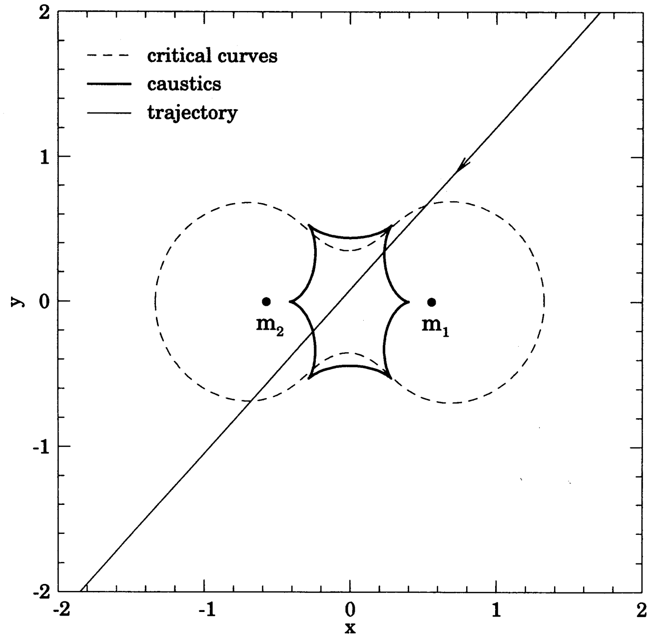

FIG. 3.—Geometry of the best-fit binary microlens model. The two components are labeled as two black dots. The caustics (*thick solid*) and the critical curves (*dashed*) are both projected onto the source plane. The trajectory of the source is indicated as a straight line with an arrow indicating the direction of the motion. Both axes are in units of the Einstein radius ($R_{\rm E} \approx 10$ AU) in the source plane.

From the composite colors observed in the low, normal state we can put some limits on the components of such a blend. The combined magnitudes of the low state are $V = 19.4$ and $I = 17.5$. Thus the additional light has $I = 18.4$ while the lensed star $I = 18.1$. Assuming that the lensed star should be in the Galactic bulge its $V-I$ color should not exceed 2.5 mag (see CMD in Udalski et al. 1993b). Thus we can set a lower limit on the colors of the source of the additional light: $V > 19.8$ and $V-I > 1.4$, and an upper limit on its intrinsic color: $(V-I)_0 > 0.9$, where we have used the extinction for the Baade's Window field BW8, $E(V-I) = 0.55$ (Paczyński et al. 1994).

If the additional light comes from the binary lensing system itself, both components of the system should have similar spectral type, as the mass ratio is close to one. Thus the color limitation indicates that both components have spectral type later than K1 and their masses must be smaller than 0.8 $M_\odot$, assuming normal, solar metallicity main-sequence stars. On the other hand, two K1 type stars cannot be further from us than 4–5 kpc to have the observed V luminosity (assuming 1–1.2 mag extinction). Fainter objects must have been located much closer. For example, early M-type components would be only 1–2 kpc from us—a distance that makes lensing very unlikely. Taking both limits together we conclude that if the lensing binary is the only source of additional light then it must consist of two K-type stars with masses 0.5–0.8 $M_\odot$ located in the Galactic disk at a distance of 3–5 kpc.

The second possibility for the additional light is a very close ($<0''\!.5$) optical companion of the lensed star. In this case we can put only the following constraint on the lensed star: $V = 19.4$, $V-I = 1.3$ if the companion is very red and does not contribute to the V band. The most likely situation is a bulge companion with color $V-I = 1.6$ which gives $V = 20.3$ and $V-I = 2.2$. In either case the lensed star is a typical Galactic bulge star (Udalski et al. 1993b).

We now check whether the assumption of the lensed star being a point object is valid. The lensed star I-band magnitude is $I = 18.1$, and it must lie on the line ($V = 19.4$, $V - I = 1.3$) – ($V = 20.6$, $V - I = 2.5$) on the CMD. Following Paczyński et al. (1994), the extinction to the BW8 field and color excess are $A_V = 1.4$, $E(V-I) = 0.55$, respectively. The absolute V magnitude and intrinsic color of the source can be estimated to be in the range $M_V = 3.5$, $(V-I)_0 = 0.75$ to $M_V = 4.7$, $(V-I)_0 = 1.9$, where we have assumed that the distance to the bulge is 8 kpc. That corresponds to a slightly evolved G-M spectral type main-sequence star. The upper limit for the radius of such a star can be safely set to be $R_* = 10R_\odot = 7 \times 10^{11}$ cm. We can now compare this with the Einstein radius, which is given by

$$R_E = V_t t_E = 1.4 \times 10^{14} \text{ cm } \frac{V_t}{200 \text{ km s}^{-1}}, \quad (2)$$

where V_t is the total transverse velocity of the lens, observer, and source projected onto the source plane. The source radius is at least one order of magnitude smaller than the intercaustic spacing (see Fig. 3). The point source approximation is excellent except for the points close to the fold caustics. For these points, the source size sets a limit on the maximum magnification, $A_{max} \approx (R_*/R_E)^{-1/2}$. For OGLE No. 7, this does not affect the fit. This can also be seen in Figure 2, where the light curve shown is obtained for a star with radius $R_* = 5 R_\odot$. The resulting light curve fits the data as well as that of a point source.

As $R_E \propto M^{1/2}$, we can estimate the total mass of the binary lens (cf. Paczyński 1986)

$$M = 1.3 M_\odot \left(\frac{V_t}{200 \text{ km s}^{-1}}\right)^2 \left(\frac{x}{1-x}\right), \quad (3)$$

where $x = D_L/D_S$ is the ratio of the distances to the lens and the lensed star. We have shown that if the additional light comes from the binary lens, then the lensing object must be located in the disk, about 4 kpc from us ($x = 0.5$) where the most likely velocity is about 200 km s^{-1}. Equation (3) then gives a total mass of 1.3 $M_\odot$, that is, about 0.7 $M_\odot$ for each component in excellent agreement with the color constraints.

5. DISCUSSION

In the previous section we considered possible explanations of the strange photometric behavior of OGLE No. 7. It seems that the binary microlens model is the most likely explanation, as the model reproduces well the light variations and explains the observed colors of the star. However, we cannot rule out the possibility that we have discovered a completely new type of variable star, and that the binary microlens model is simply a false positive (cf. Mao & Di Stefano 1995). However, such a false positive seems unlikely.

Generally speaking, there may be multiple binary lens fits to a given light curve, especially one with small amplitude (Mao & Di Stefano 1995). Fortunately, OGLE No. 7 is a strong, high-amplitude event with distinctive features; correspondingly the models are well constrained. The best model presented here is significantly better than any of the other fits we have found. We believe that it is probably the unique solution. Our model not only provides a good fit to the observed light curve, it also makes a very specific prediction, that is, the spectrum should be a composite of at least two sources of comparable brightness. If the extra light in our model is contributed by an additional source close to the lensed star, then the additional source can potentially be resolved by high resolution imaging with *HST*. In addition, the source is likely to have a different radial velocity from the lensed star. The velocity difference may not be large, therefore high-dispersion instruments (e.g., Keck telescope) are needed for detection. On the other hand, if the binary lens contributed the extra light, then the circular motion of the two components (~ 10 km s^{-1}) can be measured spectroscopically. This will in turn reliably determine the other parameters (including the lens mass) in our model. There is one more test which distinguishes the lensing model from other kinds of variability. The microlensing event should not repeat, as the chance of the same star being lensed more than once is negligible. Thus if brightening of OGLE No. 7 repeats in our long-term monitoring of the source, the microlens model will have to be rejected.

Mao & Paczyński (1991) estimated that 10% of the events may exhibit binary features. With the implementation of the early warning system of OGLE (Udalski et al. 1994b) most of these binary events can be caught in the early stages and therefore be well sampled in the bright caustic crossing phase. For the microlens model of OGLE No. 7, the caustic crossing lasted for only $5 \times R_*/(5 R_\odot)$ hr. This indicates that frequent sampling is very important. A densely sampled caustic crossing event will allow us to resolve the source structure more easily than for the case of a single lens (Gould 1994; Nemiroff & Wickramasinghe 1994; Witt & Mao 1994). In addition, relatively small changes in the lensing parameters will induce large change in the light curve; therefore, a well-sampled binary lens light can be used to potentially determine all the parameters accurately, including the mass of the lenses.

Photometry of OGLE No. 7 and other microlensing events, as well as a regularly updated OGLE status report, can be found over the Internet at host "sirius.astrouw.edu.pl" (148.81.8.1), using the "anonymous ftp" service (directory "ogle," files "README," "ogle.status," "early.warning"). Information on the recent OGLE status is also available via the World Wide Web, WWW: "http://www.astrouw.edu.pl/."

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