Mass Estimates for Some of the Binary Lenses in OGLE-III Database

M. Jarośnyński¹, A. Udalski¹, M. Kubiak¹, M.K. Szymański¹, G. Pietrzyński¹,², I. Soszyński¹,², K. Żebruń¹, O. Szewczyk¹ and Ł. Wyrzykowski³

¹Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland
e-mail: (mj,udalski,mk,msz,pietrzyn,soszyn,zebrun,szewczyk,wyrzykow)@astrouw.edu.pl
²Universidad de Concepción, Departamento de Física, Casilla 160–C, Concepción, Chile

ABSTRACT

We model binary microlensing events OGLE 2003-BLG-170, 267, and 291. Source angular sizes are measured for the events 267 and 291. Model fits to the light curves give parallaxes for the events 267 and 291, and relative source sizes for 170 and 267. Self-consistency arguments provide extra limits on the models of the event 291. As a result we obtain likelihood estimate of the lens mass for the event 170, mass measurement based on angular size and parallax for 267, and narrow limits on mass in the case of 291. Brown dwarfs are most likely candidates for some of the lens components. The influence of the binary lens rotation and the Earth parallax may be important but hard to distinguish when modeling relatively short lasting binary lens events.

1 Introduction

Among several microlensing events discovered by the Early Warning System (EWS - Udalski et al. 1994b, Udalski 2003a) of the third phase of the Optical Gravitational Lens Experiment (OGLE-III) three binary lenses of 2003 season (2003-BLG-170, 2003-BLG-267 and 2003-BLG-291 – compare Jaroszyński et al. 2004, hereafter Paper II) deserve a special treatment. Events 170 and 267 have caustic crossings covered by observations, which makes them possible candidates for mass measurements. Event 291 is interesting due to its complexity: its light curve might be understood as a result of a cusp approach followed by a caustic crossing after several months.

The first microlensing phenomenon interpreted as being due to the binary system was the event OGLE-7 (Udalski et al. 1994a). Several binary lens events with good light curve coverage were used to study the atmospheres of the source stars (e.g., Albrow et al. 1999b) or to constrain the lensing system parameters (e.g., Albrow et al. 1999a). The first lens mass measurement was obtained by An et al. (2002) based on a binary lens event with combined effects of parallax motion and caustic crossing.

The lensing by two point masses was studied by Schneider and Weiss (1986). Various aspects of binary lens modeling were described (among others) by Gould and Loeb (1992), Bennett and Rhie (1996), Gaudi and Gould (1997), Dominik (1999), Albrow et al. (1999c), and Graff and Gould (2002). Some basic ideas for binary lens analysis can be found in the review article by Paczyński (1996).

In a typical situation one attempts to fit only the simplified six* parameter binary lens models. Such models assume the source to be point-like and neglect

*We count only the parameters defining the binary and the source track. Another two parameters are necessary to give the source and blend fluxes.
the effect of the Earth and binary orbital motions. In fact, majority of our models in the past (Jaroszyński 2002 – hereafter Paper I and Paper II) belonged to this class.

Due to the high data quality in cases of interest we are able to fit more sophisticated models to the light curves, including the influence of the source finite size, parallax effect, and, to some extend, the rotation of the binary lens. These effects are not equally important in all three cases, but we check all possibilities.

The calculation of lens magnification for extended sources, especially when they cross caustics, is a time consuming numerical problem. The burden becomes even heavier for events which have well covered caustic crossing and so the most unpleasant case of calculations is required for high number of source locations. We basically use the magnification calculation in the lens plane (Dominik 1995, 1998, Bennett and Rhie 1996, Gould and Gaucherel 1997) following the numerical algorithms of Mao and Loeb (2001).

While using exact numerical methods is necessary in the final part of the model optimization, in some cases one can use faster, approximate calculation schemes to obtain solutions close to the optimal.

In the next Section we describe our models. Section 3 describes the three events and shows the best fits to observations obtained under various assumptions. The discussion follows in the last Section.

2 Technical Approach

Our basic approach to modeling binary microlensing light curves is described in Papers I and II. We repeat some of the definitions here for completeness and because different groups tend to use somewhat different parameterizations. Inclusion of parallax effects and binary rotation to our models requires some refinements and introduction of extra parameters.

The search for solutions is based on $\chi^2$ minimization method for the light curves. It is convenient to model the flux at the time $t_i$ as:

$$F_i = F(t_i) = A(t_i) \times F_s + F_b$$

where $F_s$ is the flux of the source being lensed, $F_b$ the blended flux (from the source close neighbors and possibly the lens), and the combination $F_b + F_s = F_0$ is the total flux, measured long before or long after the event. The lens magnification (amplification) of the source $A(t_i) = A(t_i; p_j)$ depends on the set of model parameters $p_j$. Using this notation one has for the $\chi^2$:

$$\chi^2 = \sum_{i=1}^{N} \frac{(A_i F_s + F_b - F_i)^2}{\sigma_i^2}$$

where $\sigma_i$ are the rescaled errors of the flux measurement taken from the DIA photometry. The dependence of $\chi^2$ on the binary lens parameters $p_j$ is complicated, while the dependence on the source/blend fluxes is quadratic. The subset of equations $\partial^2 \chi^2/\partial F_s = 0; \partial^2 \chi^2/\partial F_b = 0$ can be solved algebraically, giving $F_s = F_s(p_j; \{F_i\})$ and $F_b = F_b(p_j; \{F_i\})$ thus effectively reducing the dimension of the parameter space. In some cases this approach may give unphysical solutions with negative blended flux ($F_b < 0$). We reject all such unphysical models as final results of minimization scheme; paths to minima through unphysical regions of parameter space are not prohibited.
The binary system consists of two masses \( m_1 \) and \( m_2 \), where by convention \( m_1 \leq m_2 \). The Einstein ring radius of the binary lens is defined as:

\[
    r_E = \sqrt{\frac{4G(m_1 + m_2)}{c^2}} \frac{d_{\text{OL}} d_{\text{LS}}}{d_{\text{OS}}} \equiv d_{\text{OL}} \Theta_E \approx 8 \text{ AU} \sqrt{\frac{m_1 + m_2}{M_\odot}} x(1 - x) \tag{3}
\]

where \( G \) is the constant of gravity, \( c \) is the speed of light, \( d_{\text{OL}} \) is the observer–lens distance, \( d_{\text{LS}} \) is the lens–source distance, and \( d_{\text{OS}} \equiv d_{\text{OL}} + d_{\text{LS}} \) is the distance between the observer and the source, and \( \Theta_E \) is the angular size of the Einstein ring. The approximate dependence of \( r_E \) on binary mass and dimensionless distance to the lens \( x \equiv d_{\text{OL}}/d_{\text{OS}} \) is given for the future use. The distance \( d_{\text{OS}} = 8 \text{ kpc} \) is assumed in the calculation. The Einstein radius serves as a length unit in the lens plane.

The binary system itself is described by two parameters: \( q \equiv m_1/m_2 \) (0 < \( q \) ≤ 1) – the binary mass ratio, and \( d \) – binary separation expressed in \( r_E \) units. If one neglects the binary motion, its separation and orientation in the sky remain constant. The influence of binary rotation is discussed below. We neglect the possibility that the source itself belongs to a star system and assume that it moves with constant velocity relative to the lens center of mass, as observed by a heliocentric observer. Thus to a heliocentric observer the source path projected into the lens plane is a straight line. One may define: \( b \) – the impact parameter, the distance between the source trajectory and the binary center of mass; \( t_0 \) – the time of the source passage by the center of mass; \( \beta \) – the angle between the source trajectory and the line joining binary components measured at \( t_0 \); \( t_E \) – the Einstein time in which source travels a distance equal to \( r_E \). The dimensionless source radius \( r_s \equiv \Theta_*/\Theta_E \) is the ratio of the source and the Einstein ring angular sizes. This is the complete list of seven binary lens parameters used in simplified models.

The orbital motion of the Earth introduces an extra periodic component to the source motion relative to the lens. The amplitude of this effect depends on the relative size of the Earth orbit and the Einstein radius projected into the observer’s plane:

\[
    \pi_E = \frac{1\text{AU}}{r_E}\quad \text{where} \quad \tilde{r}_E \equiv r_E \frac{d_{\text{OS}}}{d_{\text{LS}}} \tag{4}
\]

The orientation of the source path as seen by a heliocentric observer relative to the line of constant ecliptic latitude in the sky, \( \psi \), has an impact on the shape of the source trajectory. Sources in the Galactic bulge have small ecliptic latitudes, so the parallax-induced motion along the ecliptic strongly dominates its perpendicular component.

The binary lens orbit can be fully defined by six parameters giving its size, eccentricity, orientation in space and rotation period. The fit of all parameters would probably be possible only in cases, where the strong source amplification lasts for time comparable to the revolution of the binary. The binary projected into the sky is fully characterized by its mass ratio, which remains constant, separation (\( d \)), and position angle (\( \beta \)). In the first order approximation one may assume the latter parameters to change linearly with time:

\[
    \beta(t) = \beta_0 + \dot{\beta}(t - t_0) \quad d(t) = d_0 + \dot{d}(t - t_0) \tag{5}
\]

where \( d_0, \beta_0 \) are the parameter values at the time \( t_0 \), and \( \dot{d}, \dot{\beta} \) are their rates of change.

The simultaneous measurement of parallax effect and source angular radius may be used to estimate the masses of the binary components (An et al. 2002).
Using Eqs. (3) and (4) and the definition of the dimensionless source size \( r_s \) one has:

\[
m_1 + m_2 = \frac{c^2}{4G} \hat{r}_E \Theta_E = \frac{c^2}{4G} \frac{1 \text{ AU}}{\pi E} \Theta_E \quad \text{(6)}
\]

Since the binary orbit parameters are not known, one can only roughly estimate its orbital period. One has:

\[
P_1 \approx 1 \text{ y} \left( \frac{d r_E}{1 \text{ AU}} \right)^{1.5} \left( \frac{m_1 + m_2}{M_\odot} \right)^{-0.5} ; \quad P_2 \approx \frac{2\pi}{\beta} \quad \text{(7)}
\]

respectively from the Kepler’s IIIrd law or from the fitted rate of position angle changes.

3 The Events – Data and Modeling

We use the OGLE III data, which are routinely reduced with difference photometry based on algorithms developed by Alard and Lupton (1998) and Alard (2000), giving high quality light curves of variable objects. The Early Warning System (EWS) of OGLE III (Udalski 2003a) automatically picks up candidate objects with microlensing-like variability. In some cases it is possible to make more observations of objects of interest (several data points per night), as compared to the usual survey mode (one per night). The events we describe here belong to this class. All our events were already analyzed in Paper II using simplified (6 or 7 parameter) models of binary lenses.

The large majority of observations were performed in \( I \) filter only. The field of 2003-BLG-291 has a few measurements in \( V \) filter acquired in 2004, when the source was amplified. Other observations of fields of interest in \( V \) were obtained in 2005.

3.1 OGLE 2003-BLG-170

The event shows three distinct maxima in its light curve. The first may be interpreted as a result of a cusp approach, and the remaining as a following two caustic crossings with a characteristic "U-shaped" fragment of the light curve between them. The caustic crossings are well covered. The source is rather faint (\( I_0 = 18.593 \) mag) and its significant (i.e., stronger than 0.3 mag) lens magnification lasts for only 26 days. Due to the proximity of a brighter star the measurement of the source angular size based on color determination has not been possible in this case.

We have tried to improve our fit of the event light curve described in Paper II using models including parallax and/or rotation. While some of the models with parallax have formally lower \( \chi^2 \) compared to our best 7 parameter model, the difference is insignificant (\( \leq 0.5 \)). Apparently neither parallax nor rotation could appreciably influence the light curve of this short lasting event. Our calculations give slightly improved 7 parameter model of the event, very close to the one presented in Paper II.

The parallax measurement for this event is impossible, but the time resolved caustic crossings observations allow to estimate the Einstein radius projected into the source plane (Eq. 6). Our fit gives the flux ratio \( F_s/F_0 = 0.735 \), so the source apparent luminosity is \( I_0 = 18.927 \pm 0.004 \) and the blend has \( I_0 = 20.03 \pm 0.01 \). Assuming the source to be at the distance of 8 kpc and using OGLE-II extinction maps (Udalski 2003b; Sumi 2004) we obtain \( M_I = 3.54 \pm 0.04 \), where
the extinction is the main source of error. Thus the source star is \( \approx 0.5 \text{ mag} \) brighter than the Sun. If it is a main sequence dwarf, it is roughly 10\% larger than the Sun, and we estimate its radius to be \( R_* = (0.005 \pm 0.0005) \text{ AU} \). Using \( r_s = 0.00267 \) from the best fit one gets the masses of the lens components as a function of the relative lens distance \( x \equiv d_{OL}/d_{OS} \). For the fitted mass ratio \( q = 0.789 \) one has:

\[
m_1 + m_2 = (0.024 \, M_{\odot} + 0.030 \, M_{\odot}) \frac{x}{1-x} \left( \frac{R_*}{0.005 \, \text{AU}} \right)^2 \frac{8 \, \text{kpc}}{d_{OS}},
\]

The requirement that the lens should be fainter than \( I_b = 20.03 \) is met for \( x \leq 0.95 \) \((d_{OL} \leq 7.6 \, \text{kpc})\). The lens velocity perpendicular to the source–observer line,

\[
v_\perp \equiv \frac{r_E}{t_E} = 203 \frac{\text{km}}{s} \frac{R_*}{0.005 \, \text{AU}}
\]

is typical for an object belonging to the Galactic disk. Using Han and Gould (1996) model of the Galaxy we check the likelihood of measuring the obtained value of the relative lens velocity depending on the distance to the lens. The observer’s motion is a combination of Sun and Earth motions. We take into account the peculiar velocity of the Sun and the Earth velocity on June 6th (between caustic crossings). The lens and source velocities are drawn at random from distributions adopted in the Galaxy model for stars of the disk and bulge respectively. The relative likelihood function for the source distance is shown in Fig. 2. The measurement of relative velocity gives rather wide limits for the possible distance to the lens: with 90\% probability it is \( 5.84^{+1.76}_{-3.34} \) kpc. The corresponding masses of the lens components are: \( m_1 = 0.065^{+0.039}_{-0.054} \, M_{\odot} \), \( m_2 = 0.08^{+0.49}_{-0.054} \, M_{\odot} \). Most likely we deal with two brown dwarfs at the distance not exceeding \( \approx 6 \) kpc, but dwarfs with masses \( \approx 0.5 \, M_{\odot} \) are not excluded.

### 3.2 OGLE 2003-BLG-267

The light curve of 2003-BLG-267 has four distinct maxima, which were observed between HJD = 2452837 and 2452852 (July/August 2003). This shape may be interpreted (within binary lens hypothesis) as due to the source cusp approach, two caustic crossings and another cusp approach. The caustic crossings are well
Fig. 2. The combined mass of the lens (solid line) and the likelihood function for its distance (dashed) for the event 2003-BLG-170. The mass plot is continued to 7.6 kpc only, since larger lens distances are excluded by the limit on lens luminosity. The source distance 8 kpc and size 0.005 AU are assumed. Dotted lines show the boundaries of the 90% likelihood region.

covered. The cusp approaches are not particularly close, so the source remains 1 to 2 mag fainter compared to its observed flux during the crossings. The amplification $\geq 0.3$ mag above the base brightness lasts for about 80 days. The angular radius of the source based on $V-I$ vs. $V-K$ color relation of Bessell and Brett (1988) and color–angular size calibration of van Belle (1999) could only be obtained under the assumption that the blend is negligible. Fortunately the result $\Theta_* = 0.67 \pm 0.15 \mu$as is applicable to our best models (see below) since the fits give practically vanishing blended fluxes.

The standard 7 parameter modeling of the event gives a model light curve with systematically displaced wings (cf. Fig. 3). This is true for both close binary (model 1 in Table 1) and wide binary lenses (model 2). We do not show any plots regarding wide binary models since they give much worse fits of the light curve.

The systematic differences between the model light curve and observations suggest that some effects neglected in modeling are in fact important. Therefore, we use models with parallax effect, binary rotation and their combination what substantially improves the model quality, at least for some close binary lenses. For the wide binary lenses the inclusion of parallax and/or rotation helps in some cases, but the fits remain worse than for the best 7 parameter model using a close binary.

The following figures show the source paths for various models. The estimates of the binary component masses, the period of revolution and the lens distance are also given in Table 1.

Models taking into account the Earth motion (but not the binary rotation) improve the fit and give a high value of parallax. The best model of this kind (model 3 in Table 1) predicts very small mass and rather short rotation period of the binary. The estimated rotation rate of this model is in fact higher than in the models taking rotation into account. Since the lower rotation rate of the other
models has a strong influence on the modeling, our model is not selfconsistent, unless the binary is viewed at very specific orientation and phase of the orbital motion – a rather unlikely situation.

The models with rotation (but no parallax) represent another improvement compared to the standard approach. The direct lens mass estimate is not possible in this case. The fit of the relative source size and measurement of its angular size may be used to estimate the Einstein radius itself (and the binary component masses) as a function of the lens distance. This allows to derive another binary period estimate. The projection and orientation effects make the simple comparison of the two rotation rate estimates inconclusive.

Models taking into account parallax and/or rotation give substantially better fits compared to standard seven parameter models. There is an elongated region in \((\pi_E, \dot{\beta})\) plane running along the straight line given by

\[
\frac{\pi_E}{2.51} + \frac{\dot{\beta}}{186^\circ/\text{yr}} \approx 1
\]  

(10)
which contains the high quality models. The best fit has parallax $\pi_E = 0.25$ and rotation $\dot{\beta} = 168^\circ \, y^{-1}$. Since there are many local minima of $\chi^2$ in the parameter space, the confidence regions for $\pi_E$ are complicated. The 68% confidence region is limited to the close vicinity of the best fit. The 95% confidence region includes also a separate part with $\pi_E \approx 0$. Finally 99% confidence region consists of several other pieces around $\pi_E \approx 0.074, 0.15, 0.35, \text{and } 0.63$. Thus the mathematical modeling gives rather wide limits on possible value of parallax parameter.

The flux ratio for the best fit model $F_s/F_0 = 0.994$ is close to unity and the same is true for all other models of comparable quality. Thus we can make use of the estimate of the source angular size.

Assuming that the lens consists of two brown dwarfs or two main sequence stars, and using dependence of the mass on the distance to the lens (relation analogous to Eq. 8 for event 170), we estimate the apparent luminosity of the lens. The strong limit on the lens flux puts an interesting limit on the maximum distance to the lens ($d_{OL} \leq 0.92 \, d_{OS}$). Since the source size, lens location and the parallax are related (Eqs. 4–6), this limit translates also into $\pi_E \geq 0.05$. It also excludes high mass lens close to the source, unless it consists of white dwarfs, neutron stars and/or black holes.

Using the best fit model we obtain the following estimate of the lens component masses:

$$m_1 + m_2 = (0.055 \, M_\odot + 0.068 \, M_\odot) \frac{0.25}{\pi_E} \frac{\Theta_*}{0.67 \, \mu \text{as}}$$

Formal (one sigma) error of parallax fit is very low for the best model ($\pi_E = 0.24074 \pm 0.00003$), so formally the above estimate gives masses to $\approx 22\%$, error resulting from imprecise knowledge of the source size.
Using wide (99%) confidence limits on parallax (0.074 ≤ π_E ≤ 0.63) and neglecting the errors resulting from the source angular size, one obtains safe limits on the masses: m_1 = 0.055^{+0.13}_{-0.032} M_⊙ and m_2 = 0.068^{+0.16}_{-0.041} M_⊙. The corresponding limits on the lens distance are: d_{OL} = 5.44^{+1.59}_{-1.78} kpc.

Following An et al. (2002) we check the consistency of the model comparing the transverse potential and kinetic energies of the binary. Using their formalism and notation we obtain |T_⊥/K_⊥| = 3.04 for the best model, where the potential energy T_⊥ is calculated using the projected distance between the lens components instead of the true 3D quantity and similarly the kinetic energy K_⊥ neglects the unknown motion along the line of sight. Checking the value of projected energies ratio for other models within 99% confidence limits we find that |T_⊥/K_⊥| = 4.02 for π_E = 0.074, 5.83 for π_E = 0.63, and it always exceeds 3.0 within the confidence region. All these numbers are typical for a binary of almost every possible eccentricity and orientation (e.g., Fig. 12 in An et al. 2002).

The rotation of the best model is also consistent with our assumptions: the position angle of the binary changes by ≈37° during 80 days of substantial lens amplification, and by ≈3° between caustic crossings. Since the lens separation remains constant, our approximate description of the binary remains valid.

### 3.3 OGLE 2003-BLG-291

Observations of 2003 season alone could be well modeled as a single mass microlensing event. Including the data from the beginning of 2004 season, one could think of a double source model for the light curve. Finally, the rapid rise of the flux after HJD = 2453093 (2004 March 29) and characteristic behavior during the following drop of the brightness, resemble the caustic crossing event. The light curve is not complete, only the flux decrease after the first caustic crossing is covered by observations.
The observations in V filter obtained in 2004 and 2005 seasons allow the angular size measurement. Using the color–angular size relation we obtain $\Theta_\ast = 0.97 \pm 0.10 \, \mu\text{as}$.

The maximum of brightness in 2003 season had taken place 255 days before the caustic crossing in April 2004. Such a long time scale of the event forces one to use models taking parallax into account. In fact the model shown in Paper II was of this kind. We have not described it explicitly, but the source trajectory shown there in Appendix 1 would never approach the other caustic unless it were curved.

When dealing with the event, we first try to model the observations from the beginning of the 2004 season, with standard 7 parameter approach tentatively using source trajectories crossing caustics. The best agreement with observations is obtained for deltoid caustics of either close or wide binary lenses and trajectories at an angle to the line joining lens components. In the case of close binaries such lines may pass close to a triangular caustic of the system for certain choices of mass ratios, but the associated temporal amplification of the source is too short and/or too weak to resemble the light curve of 2003.

Next we try 7+2 and 7+4 parameter approaches. We start from models with deltoid caustics crossings and (using parallax and/or rotation) allow the trajectories to bend. After quite extensive search over the parameter space we obtain the best model shown in Figs. 7 and 8. This model includes parallax with substantial influence of the binary rotation. The best model with parallax but no rotation represents a significantly worse fit of the event ($\chi^2$ larger by $> 10^2$). We have not been able to obtain any realistic model with rotation but no parallax: standard 7 parameter approach is not capable of producing the event light curve which would even qualitatively match the observations.

Both caustic crossings took place during the day, so a direct measurement of the relative source size is not possible for 2003-BLG-291. The minimization of $\chi^2$ chooses nonphysically small sources (practically $r_s \to 0$). Small $r_s$ implies however (cf. Eq. 6) large angular size of the Einstein ring, small distance to the lens and its high mass. Thus the requirement that the lens should not be too bright puts a lower limit on the value of the parameter $r_s$ for given values of $q$, $\pi_E$, $F_s$, and $F_0$. 

| $\chi^2$/DOF | $q$ | $d_0$ | $r_s$ | $\pi_E$ | $\dot{\beta}$ | $m_1$ | $m_2$ | $P_1$ | $P_2$ | $d_{OL}$ |
|--------------|-----|------|------|--------|--------|------|------|------|------|--------|
| 1            | 1002./249 | 0.668 | 0.353 | 0.00085 | -   | -   | -   | -   | -   | -   |
| 2            | 1170./249 | 0.159 | 5.020 | 0.00038 | -   | -   | -   | -   | -   | -   |
| 3            | 608./247  | 0.805 | 0.553 | 0.00267 | 2.51 | -   | 0.0048 | 0.0060 | 0.73 | - | 1.49 |
| 4            | 604./247  | 0.796 | 0.554 | 0.00269 | -   | 186 | -   | -   | -   | 1.88 |
| 5            | 596./245  | 0.797 | 0.551 | 0.00266 | 0.25 | 168 | 0.052 | 0.065 | 1.66 | 2.17 | 5.44 |

Note: The table gives some of the model parameters and the results of mass, period and distance estimates where applicable. Models 1 (a close binary) and 2 (a wide binary) give the best fits obtained under the approximation excluding the effects of parallax and binary rotation. Model 3 allows for parallax, but not for rotation; model 4 includes rotation, but no parallax effect, and model 5 takes into account both effects.
For the models including rotation we check the ratio of transverse potential and kinetic energies (An et al. 2002) at the two epochs of interest, when the source approaches or crosses the caustic. This criterion makes models with relatively high velocities of binary components physically uninteresting and we do not consider them here. We choose the best of the physically plausible fits as our favored model. Its parameters with standard errors are given in Table 2. The physical limitations may introduce asymmetries to error estimates of some quantities, but we neglect this effect.

Using the best fit and the measurement of angular source size we get the estimates of the binary lens components masses:

\[ m_1 + m_2 = (0.056^{+0.006}_{-0.006} \, M_\odot + 0.090^{+0.009}_{-0.009} \, M_\odot) \frac{\Theta_*}{0.97 \mu\text{as}} \]  

(12)

\[ = 0.056^{+0.006}_{-0.006} \, M_\odot + 0.090^{+0.009}_{-0.009} \, M_\odot \]  

(13)

where the second equality takes into account also the error of the source angular size measurement. The distance to the lens can be estimated as \( d_{\text{OL}} = (0.29 \pm 0.03) \) kpc and the proper motion of the lens relative to the source as \( \mu_{\text{rel}} = \)
Fig. 8. OGLE 2003-BLG-291: the light curve based on the model including parallax effect and binary rotation (solid line). Observations of parts of 2003 and 2004 seasons are shown (error bars). The insert shows the details of caustic crossings.

\( \chi^2 = 467.0 \div 251 \quad t = 43.5 \)

(16.7 ± 1.7) mas/y, errors resulting mostly from the imprecise source size. The direction of the lens motion is opposite to the source motion shown in Fig. 7. The linear velocity of the lens, \( \approx 23 \) km/s is consistent with a peculiar velocity of an object belonging to the Galaxy disk.

4 Discussion

We have modeled three OGLE-III binary microlensing events of season 2003 trying to obtain estimates of the lens masses. Only in one case (2003-BLG-267) the relative size of the source and parallax effect can be fitted by modeling the light curve, and the angular size of the source is measured using color–color relation, which gives masses of the binary components. In the case of 2003-BLG-291 the parallax can be fitted and the source angular size is measured. The relative source size cannot be fitted directly from the optimization of the model, but the requirements that the lens must not be too bright and the binary has to be a bound system, give rather narrow limits on its value. The event 2003-BLG-170 allows only to fit the source relative size. The measurement of the source angular size can be to an extent replaced by the rough estimate of its physical size, but it requires assumptions about the nature of the source and its distance. Using this assumptions one can perform only a likelihood estimate of
Table 2
The best model of OGLE 2003-BLG-291

| $q$  | $d_0$ | $b$  | $t_0$ | $t_E$ | $r_s$  | $\pi_E$ | $\psi$ | $\dot{d}$ | $\dot{\beta}$ |
|-----|-------|------|-------|-------|-------|---------|--------|----------|-----------|
| [r_E] | [°]  | [d] | [d]   | [x10$^{-3}$] | [°]  | [r_E/y] | [°/y] |
| 0.617 | 3.04 | 184.7 | 0.50 | 2925.8 | 43.5 | 0.488 | 172.1 | 2.2 | 18.3 |
| 0.016 | 0.06 | 0.9 | 0.01 | 1.4 | 0.5 | 0.013 | 0.06 | 0.4 | 0.1 | 1.1 |

Note: The table gives all model parameters and their estimated 1-$\sigma$ errors.

the lens mass, using a model of velocity and density distributions in the Galaxy.

In the case of 2003-BLG-267 we obtain binary lens components masses of $0.055$ M$_\odot$ + $0.068$ M$_\odot$. Within 95% confidence limits the relative errors are $\approx 20\%$ and result mostly from imprecise knowledge of the source size. Higher (99%) confidence limits include substantial spread in parallax estimate which becomes the main source of error. The limits on masses become rather wide ($0.023$ to $0.19$ M$_\odot$ and $0.027$ to $0.23$ M$_\odot$, respectively) including low mass main sequence stars. Still higher masses are possible if the lens consists of compact faint objects like white dwarfs, neutron stars and/or black holes. Such object would be located very close to the source, which is extremely unlikely in the standard Galaxy models.

In the case of 2003-BLG-291 we formally obtain the narrowest limits on the lens component masses. One must however remember that our model is located on the boundary of physically acceptable region in parameter space. This means that the model is in a sense unnatural. While our model binary lens slowly changes its position angle in the sky, its separation changes are rather rapid (see Fig. 7), which makes our approximate description of the binary motion ($\dot{d} \approx$ const) marginally consistent. Probably the full modeling of the binary is necessary to describe it selfconsistently, but such an approach is beyond the scope of the present paper. It is also possible that the events of 2003 and 2004 are caused by two separate lenses, one of them a binary. Since high amplification of the source takes place at locations separated by few Einstein radii, the third body responsible for the 2003 single event does not have to influence strongly the binary responsible for the 2004 light curve. (It is certainly model dependent, but large separation is at least possible.) The most important argument against the three body hypothesis is its low a priori probability: two independent microlensing events including the same source have a chance $\approx p^2$, where $p \ll 1$ is a chance of one such event during a year. The triple lens is still another possibility which has not been checked in our investigation.

Our lens mass estimate for OGLE 2003-BLG-267 is the third such attempt (after An et al. 2002 and Kubas et al. 2005) using the parallax and source size measurements for a binary microlensing event. In our approach we take into account both parallax effect and source rotation in a way closely resembling the method of An et al. (2002). The other group (Kubas et al. 2005) neglects rotation of the lens. In the case of 2003-BLG-267 both effects play a role; to some extend one can be replaced with another which is the main source of ambiguity of our parallax measurement. This is due to the fact that the strong amplification lasts for rather a short time (80 days), so the periodic effects of
parallax do not affect the light curve, while the local bending of the trajectory can be accomplished using rotation as well.

In some (but not all) binary microlensing events the parallax and binary rotation may influence the important fragments of the source trajectory in a way hardly distinguishable in the shape of light curves. We certainly deal with such situation in our model of 2003-OGLE-267, where the quality of fits using different mixtures of parallax and rotation is almost the same. The effect is also present to some extent in modeling 2003-OGLE-291, but in this case it involves other parameters as well, and some of the concurrent solutions are physically invalid. We deal with a degeneracy, similar to better known degeneracies in single lens microlensing as described by Smith, Mao and Paczyński (2003) and Gould (2004). The binary case is more complicated, since for a similar light curve one has to reproduce a 2D trajectory of the source in the binary lens plane, instead of 1D temporal dependence of its distance from the single mass.

There are brown dwarfs candidates among binary lens components preferred by our models. In all cases the higher mass alternatives are not excluded, but in general our estimates give smaller lens masses compared to An et al. (2002) – ≈ 0.6 M⊙ and Kubas et al. (2005) – ≈ 0.5 M⊙. The events caused by low mass lenses have typically shorter time scales and the parallax effect should be rather difficult to discover, especially the periodic seasonal modulation of the signal seen in some long lasting single mass events (Mao et al. 2002, Smith et al. 2002). On the other hand the parameter πE is large for small Einstein radii, so the light curves of low mass binary events have a greater chance to be significantly influenced by parallax. It is not clear which of the contradicting effects is more important, but taking into account the parallax in cases of even short lasting binary events is worth a try.

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