OGLE 2000-BUL-43: A SPECTACULAR ONGOING PARALLAX MICROLENSING EVENT. DIFFERENCE IMAGE ANALYSIS.

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ABSTRACT

We present the photometry and theoretical models for a bulge microlensing event OGLE-2000-BUL-43. The event is very bright with $I_0 = 13.54$ mag, and has a very long time scale, $t_E = 156$ days. The long time scale and its light curve deviation from the standard shape strongly suggest that it may be affected by the parallax effect. We show that OGLE-2000-BUL-43 is the first discovered microlensing event, in which the parallax distortion is observed over a period of 2 years. Difference Image Analysis (DIA) using the PSF matching algorithm of Alard & Lupton enabled photometry accurate to 0.5%, a factor of 4.5 improvement over the standard DoPhot measurements. All photometry obtained with DIA is available electronically. Our analysis indicates that the viewing condition near Jupiter will be optimum and can lead to magnifications $\sim 50$ around January 31, 2001. These features offer a great promise for resolving the source (a K giant) and breaking the degeneracy between the lens parameters including the mass of the lens, if the event is observed with the imaging camera on the Cassini space probe.

Subject headings: gravitational microlensing — stars: individual OGLE-2000-BUL-43

1. INTRODUCTION

Gravitational microlensing was originally proposed as a method of detecting compact dark matter objects in the Galactic halo (Paczynski 1986). However, it also turned out to be an extremely useful method to study Galactic structure, mass functions of stars and potentially extra-solar planetary systems (for a review, see Paczyński 1996). Most microlensing events are well described by the standard light curve (e.g., Paczyński 1986). Unfortunately, from these light curves, one can only derive a single physical constraint, namely the Einstein radius crossing time, which involves the lens mass, various distance measures and relative velocity (see §4). This degeneracy means that the lens properties cannot be uniquely inferred. Therefore any further information on the lens configuration is of great importance. Microlensing events that exhibit parallax effects provide this type of information. Such events were predicted by Refsdal (1966) and Gould (1992). The first case was reported by the MACHO collaboration toward the Galactic bulge (Alcock et al. 1995), and the second case (toward Carina) was discovered by the OGLE collaboration and reported in Mao (1999). In this paper, we report a new parallax microlensing event, OGLE-2000-BUL-43. This bulge event was caught well ahead of the peak by the Early Warning System (Udalski et al. 1994), and attracted attention due to its extreme brightness and a very long time scale.

The orbital velocity of the Earth is typically small compared to the relative velocity of the microlensing illumination pattern ($\sim 200$ km s$^{-1}$) at the observers plane. Combined with typical distances to the source and to the lens this results in very small parallax distortions, if detectable at all. Therefore the photometric accuracy is of crucial importance here. We use the Difference Image Analysis technique to obtain the light curves of the OGLE-2000-BUL-43 event. Our DIA method is based on the recently developed optimal PSF matching algorithm (Alard & Lupton 1998; Alard 2000). Unlike other methods that use divisions in the Fourier space, the Alard & Lupton method operates directly in the real space. Additionally it is not required to know the PSF of each image to determine the convolution kernel. Wozniak (2000, hereafter Paper I) tested the method on large samples and showed that the error distribution is Gaussian to better than 99%. Compared to the standard DoPhot photometry (Schechter, Mateo, & Saha 1993), the scatter was always improved by at least a factor of 2–3 and frames taken at even worst seeing conditions gave good photometric points. Because the event is so bright (base line magnitude $I = 13.54$, $V = 15.65$, peak magnification $A \simeq 6.3$), and still in progress, we strongly encourage followup observations. In particular, space instruments could provide valu-
able information since for the observers on the Earth the event will be very close to the Sun near the peak. As shown in Section 4 the Cassini spacecraft\(^1\) will have much better viewing conditions of OGLE-2000-BUL-43 with peak magnification \(\approx 50\). The source would likely be resolved in this case and the lens degeneracy broken completely (Alcock et al. 1997; Dominik 1998).

The outline of the paper is as follows. In Section 2 we describe observations, in Section 3 we describe our photometric reduction method, Section 4 contains the details of model fitting and predicted viewing conditions, and finally in Section 5, we discuss the implications of our results.

2. OBSERVATIONS

All observations presented in this paper were carried out during the second phase of the OGLE experiment with the 1.3-m Warsaw telescope at the Las Campanas Observatory, Chile, which is operated by the Carnegie Institution of Washington. The telescope was equipped with the “first generation” camera with a SITe 2048 \(\times\) 2048 CCD detector working in the drift-scan mode. The pixel size was 24 \(\mu\)m giving the scale of 0.417'' per pixel. Observations of the Galactic bulge fields were performed in the “medium” reading mode of the CCD detector with the gain 7.1 e\(^-\)/ADU and readout noise about 6.3 e\(^-\). Details of the instrumentation setup can be found in Udalski, Kubia\k & Szymański (1997).

The OGLE-2000-BUL-43 event was detected by the OGLE Early Warning System (Udalski et al. 1994) in mid-2000. Equatorial coordinates of the event for 2000.0 epoch are: \(RA = 272^\circ 179\), \(DEC = -32^\circ 411\), ecliptic coordinates are \(\lambda = 271^\circ 863\), \(\beta = -8^\circ 986\) and Galactic coordinates are \(l = 359^\circ 467\), \(b = -6^\circ 036\). Figure 1 is a finding chart showing the 120'' \(\times\) 120'' region centered on the event. Observations of this field started in March 1997, and continued until November 22, 2000. Bulge observing season usually ends at the beginning of November, therefore the latest observations of OGLE-2000-BUL-43 were made in difficult conditions with the object setting shortly after the sunset, when the sky is still quite bright. Fortunately the source was bright enough so that poor seeing and high backgrounds were not a significant problem in the DIA analysis.

The majority of the OGLE-II frames are taken in the I-band. Udalski et al. (2000) gives full details of the standard OGLE observing techniques and the DoPhot photometry data is available from OGLE web site at http://www.astroww.edu.pl/~ogle/ogle2/ews/ews.html.

3. PHOTOMETRY

Our analysis includes 330 I-band observations of the BUL_SC7 field. We used the DIA pipeline designed and tuned for the OGLE bulge data by Woźniak (2000) based on the algorithm from Alard & Lupton (1998) and Alard (2000). This software handles PSF variations in drift-scan images by polynomial fits. Even then it is required that the frames are subdivided into 512 \(\times\) 128 pixel strips because PSF variability along the direction of the scan is much faster than across the frame. The object of interest turned out to be not too far from the center of one of the subframes selected automatically, therefore we basically adopted the standard pipeline output for that piece of the sky without the need to run the software on the full format. Minor modifications included more careful preparation of the reference image and calibration of the counts in terms of standard magnitude system.

First from the full data set for the BUL_SC7 field we selected 20 best frames with best seeing, small relative shifts and low background level. More weight was assigned to the PSF shape and quality of telescope tracking in the analyzed region during the selection process. These frames were co-added to create a reference frame for all subsequent subtractions. Preparation of the reference image was absolutely a critical point for the quality of the final results.

Next we run the DIA pipeline for all of our data to retrieve the AC signal (variable part of the flux) of our lensed star. The software rejected only 9 frames due to very bad observing conditions or very large shifts. Our final light curve contains 321 observations. To calibrate the result on the magnitude scale we ran DoPhot on the reference image. Magnitude zero point was obtained by comparing our DoPhot photometry with the OGLE database.

The DIA light curve is shown in Figure 2. The scatter in the photometry is 0.5\% and it is dominated by systematics due to atmospheric turbulence and PSF variations. The individual error bars returned by the pipeline and rescaled according to the formula given in Woźniak (2000) proved to be overestimated by about 20–30\% when compared to the scatter around the best fit model (Section 4). Most likely this is a combined result of individual care during data processing for OGLE-2000-BUL-43 and relatively low density of stars in the BUL_SC7 field. Scalings of Woźniak (2000) derived from an automated massive photometry are averaged over all fields. The error bars reported in this paper were additionally lowered by about 30\% to provide the match between the mean error and the actual scatter in the event baseline for the first two observing seasons; after this rescaling, the \(\chi^2\) per degree of freedom is roughly one for these two seasons.

We would like to stress the fact that it is the accuracy achieved here with the DIA method which enabled a detailed study of the lens parameters. Figure 3 compares the distribution of residuals with respect to the model (see §4) for measurements with the DIA pipeline and DoPhot. The improvement using DIA technique is dramatic, with the r.m.s. scatter reduced by a factor of 4–5. Please note that our data set contains 82 more points than the DoPhot OGLE light curve, the difference is because of the lowest grade frames rejected in the standard DoPhot analysis. The DIA photometry data file is available from the OGLE anonymous FTP server: [ftp://sirius.astrouw.edu.pl/ogle/ogle2/bul3.dat.gz].

In Figure 4 we present the stellar Color-Magnitude Diagram for the BUL_SC7 field. The position of the lensed star (marked by a cross) suggests that the source is a K giant. We can estimate its stellar size as follows. Following Schlegel, Finkbeiner & Davis (1998), we adopt \(A_V = 0.92\) and \(A_I = 1.53\), so the intrinsic I-band magnitude and color of the star are \(I_0 = 12.62\) and \((V-I)_0 = 1.50\). Using the Kurucz stellar atmosphere models (Kurucz 1999) for solar metallicity stars, the intrinsic color corresponds

\(^1\)http://www.jpl.nasa.gov/cassini/
to a star with effective temperature of $T_{\text{eff}} = 4,000\text{K}$, and bolometric correction to $V_0$ is B.C. $= -1.10\text{ mag}$. Adopting a distance to the source of 7 kpc, one derives the absolute bolometric magnitude of $M_{\text{bol}} = -1.2\text{ mag}$. Combining $M_{\text{bol}}$ and $T_{\text{eff}}$, one derives the stellar radius to be $R_\star \approx 30R_\odot$.

4. MODEL

We first fit the light curve with the standard single microlens model which is sufficient to describe most microlensing events. In this model, the (point) source, the lens and the observer all move with constant spatial velocities. The standard form is given by (e.g., Paczyński 1986):

$$A(t) = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}, \quad u(t) = \sqrt{u_0^2 + \tau(t)^2},$$

(1)

where $u_0$ is the impact parameter (in units of the Einstein radius) and

$$\tau(t) = \frac{t - t_0}{t_E}, \quad t_E = \frac{r_E}{v},$$

(2)

with $t_0$ being the time of the closest approach (maximum magnification), $r_E$ the Einstein radius, $v$ the lens transverse velocity relative to the observer-source line of sight, and $t_E$ the Einstein radius crossing time. The Einstein radius on the lens plane is defined as

$$r_E = \sqrt{\frac{4GM_Dx(1-x)}{c^2}},$$

(3)

where $M$ is the lens mass, $D_x$ the distance to the source and $x = D_{d}/D_x$ is the ratio of the distance to the lens and the distance to the source. Eqs. (1) shows the well-known lens degeneracy, i.e., from a measured $t_E$, one can not infer $v$, $M$ and $x$ uniquely even if the source distance is known.

To fit the $I$-band data with the standard model, we need a minimum of four parameters, namely, $u_0, t_0, t_E, m_{I,0}$, where $m_{I,0}$ is the unlensed $I$-band magnitude of the source. Best-fit parameters (and their errors) are found by minimizing the usual $\chi^2$ using the MINUIT program in the CERN library$^3$ and are tabulated in Table 1. The resulting $\chi^2$ is 10768.7 for 317 degrees of freedom. The large $\chi^2$ indicates that the fit is unacceptable. This can also be clearly seen in Figure 2, where we have plotted the predicted light curve as the dotted line. The deviation is apparent in the 2000 observing season. In fact, upon closer examination, the model over-predicts the magnification in the 1999 season as well (see the bottom inset in Figure 2). Since the Galactic bulge fields are very crowded, there could be some blended light from a nearby unlensed source within the seeing disk of the lensed source, or there could be some light from the lens itself. So in the model we can introduce a blending parameter, $f$, which we define as the fraction of light contributed by the lensed source in the baseline ($f = 1$ if there is no blending). The inclusion of the blending parameter reduces the $\chi^2$ to 3315.2 for 316 degrees of freedom, which is better but still far from acceptable. We show below that all these discrepancies can be removed by accounting for the parallax effect.

To account for the parallax effect, we need to describe the Earth motion around the Sun. We adopt a heliocentric coordinate system with the $z$-axis toward the Ecliptic north and the $x$-axis from the Sun toward the Earth at the Vernal Equinox$^5$. The position of the Earth, to the first order of the orbital eccentricity ($e \approx 0.017$), is then (e.g., Dominik 1998 and references therein)

$$x_\oplus(t) = A(t)\cos[\xi(t) - \phi_\oplus],$$

$$y_\oplus(t) = A(t)\sin[\xi(t) - \phi_\oplus],$$

$$z_\oplus(t) = 0,$$

(4)

where

$$A(t) = AU(1 - \epsilon \cos \Phi), \quad \xi(t) = \Phi + 2\epsilon \sin \Phi$$

(5)

with $\Phi = 2\pi(t - t_0)/T, \quad T = 1\text{ yr}$, and $\phi_\oplus \approx 75.98^\circ$ is the longitude difference between the Perihelion ($t_\oplus = 1546.708$) and the Vernal Equinox ($t = JD = 2450000 = 1623.816$) for J2000. The line of sight in the heliocentric coordinate system is as usual described by two angular polar coordinates $(\phi, \chi)$. These two angles are related to the geocentric ecliptic coordinates $(\lambda, \beta)$ by $\chi = \beta$, and $\phi = \pi + \lambda$. Again, for OGLE-2000-BUL-43, $\beta = -8.986^\circ$, and $\lambda = 271.863^\circ$ (see, e.g., Lang 1981 for conversions between different coordinate systems).

To describe the lens parallax effect, we find it more intuitive to use the natural formalism as advocated by Gould (2000), i.e., we project the usual lensing quantities into the observer (and ecliptic) plane. The line of sight vector is given by $\hat{n} = (\cos \chi \cos \phi, \cos \chi \sin \phi, \sin \chi)$ in the heliocentric coordinate system. For a vector, $\vec{r}$, the component perpendicular to the line of sight is given by $\vec{r}_\perp = \vec{r} - (\vec{r} \cdot \hat{n})\hat{n}$. For example, the perpendicular component of the Earth position is $\vec{r}_{\oplus, \perp} = \vec{r}_\oplus - (\vec{r}_\oplus \cdot \hat{n})\hat{n}$. Using the expressions of $\vec{r}_\perp$ and $\hat{n}$, one can show that a circle in the lens plane ($\vec{r}_\perp = R^2$) would be mapped into an ellipse in the ecliptic plane. The ellipse is given by

$$r = \frac{R}{\sqrt{1 - \cos^2 \chi \cos^2 (\Theta - \phi)}},$$

(6)

where $\Theta$ is the polar angle in the ecliptic plane. The minor axis and major axis for the ellipse are $R$ and $R/\sin \chi$, respectively.

The lens trajectory is described by two parameters, the dimensionless impact parameter, $u_0$, and the angle, $\theta$, between the heliocentric ecliptic $x$-axis and the normal to the trajectory. Note that $u_0$ is now more appropriately the minimum distance between the Sun-source line and the lens trajectory. For convenience, we define the Sun to be on the left-hand side of the lens trajectory for $u_0 > 0$. The lens position (in physical units) projected into the ecliptic plane, $\vec{r}_L = (x_L, y_L, 0)$, as a function of time, is given by

$$x_L = u_0 \vec{r}_E \cos \theta - \tau v_{E,P} \sin \theta,$$

$$y_L = u_0 \vec{r}_E \sin \theta + \tau v_{E,P} \cos \theta,$$

$$z_L = 0,$$

(7)

$^3$http://www.info.cern.ch/asd/cernlib/

$^5$Another commonly used heliocentric system (e.g., in the Astronomical Almanac 2000) has the $x$-axis opposite to our definition.
where $\tau$ is again defined in eq. (2), $\hat{r}_E = r_E/(1 - x)$ is the Einstein radius projected onto the observer plane, and $r_{E,p} = \hat{r}_E/\sqrt{1 - \cos^2 \chi \sin^2 (\pi/2 + \theta - \phi)}$ is the Einstein radius projected into the ecliptic plane in the direction of the lens trajectory. The expression of $r_{E,p}$ can be derived using eq. (3) with $\Theta = \pi/2 + \theta$, where the factor $\pi/2$ arises because $\theta$ is defined as the angle between the normal to the trajectory and the $x$-axis. We denote the vector from the lens position (projected into the ecliptic plane) toward the Earth as $\delta \vec{r} = \hat{r}_E - \hat{r}_L$. The component of $\delta \vec{r}$ perpendicular to the line of sight is $\delta \vec{r}_\perp = \delta \vec{r} - (\delta \vec{r} \cdot \hat{n}) \hat{n}$. The magnification can then be calculated using eq. (1) with $u^2 = (\delta \vec{r}_\perp/\hat{r}_E)^2$.

In total, we need seven parameters $(u_0, t_0, t_E, m_\perp, \hat{r}_E, \theta, f)$ to describe the parallax effect with blending. These parameters are again found by minimizing the $\chi^2$. In table 1, we list the best fit parameters. The $\chi^2$ is now drastically reduced to 374.7 for 314 degrees of freedom. The model is shown in Figure 2 as the solid line. As can be seen, the model fits the data points very well. Notice that the model requires only a marginally significant blending with $f = 0.91 \pm 0.05$; this is expected since the source star is very bright, and it appears unlikely that any additional source can contribute substantially to the total light.

The parallax signature of OGLE-2000-BUL-43 indicates that the magnification is a strong function of the observer position in the solar system. Figure 5 shows the illumination pattern on Jan. 1, 2001, 0UT. The two elliptical curves are iso-magnification contours for $A = 1.342$ and 4, respectively; the outer contour with $A = 1.342$ corresponds to the Einstein ‘ring’ in the ecliptic plane. It appears as an ellipse in Figures 5 and 7 because the ecliptic plane is not perpendicular to the source direction (cf. eq. 1). Various filled dots indicate the positions of the source, Earth, Jupiter and Saturn on this date. From this figure, one can see that the inner contour nearly coincides with the position of Jupiter on this date, hence an observer on the Jupiter will see a magnification of about 4. The open dots indicate the positions of the source and the planets every half a year in the future. Note that as the lens moves along its trajectory, the whole illumination pattern (iso-magnification contours) follows it.

5. DISCUSSION

OGLE-2000-BUL-43 is the longest microlensing event observed by the OGLE project. It is also the first event, in which the parallax effect is observed over a 2 year period, making the association of the acceleration term with the motion of the Earth unambiguous. Photometric accuracy at the 0.5% level enabled a detailed study of the event parameters partly removing the degeneracy between the mass, velocity and distance. Using eq. (2) and $\hat{r}_E = r_E/(1 - x) \approx 3.6\text{AU}$, we obtain the lens mass as a function of the lens distance to the source

$$M = \frac{1 - x}{x} \frac{\hat{r}_E^2 c^2}{4G D_s} \approx 0.23 M_\odot \frac{1 - x}{x} \frac{7\text{kpc}}{D_s},$$

and the transverse velocity is $v = (1 - x) \hat{r}_E / t_E \approx 40(1 - x)\text{km\,s}^{-1}$. So the lens is slow moving, and unless it is unusually close to us, its mass is expected to be small.

Several spacecrafts still have the possibility of observing this event from space. In particular the Cassini probe is currently approaching the Jupiter, for a fly-by acceleration on its way to Saturn. In Figure 6 we show the light curve of OGLE-2000-BUL-43 for an observer near the Jupiter, mimicking the fly-by observations from Cassini. The light curve shows a spectacular peak at JD=2451940.5 (Jan 31, 2001). It would be therefore extremely interesting to observe this event using the cameras on board Cassini. We could even consider a confirmation of the predictions from Figure 6 to be an ultimate proof of our understanding of the microlensing geometry. This is particularly important since the lens model may not be unique. For example, we found another model that has $\chi^2 = 382.8$ but with the blending parameter $f = 0.77$. This model predicts a much lower peak for an observer at the Jupiter. However, this model appears physically unlikely since the source star is so bright that one would expect $f$ close to 1, as found in our best fit model.

Figure 7 indicates that the position of Jupiter with respect to the illumination pattern will lead to a very high magnification near maximum for hypothetical Cassini observations. The large source size (see section Photometry) makes it even more likely that the light curve modification due to the finite source size could be detectable, thus providing one more constraint on the physics. The inset in Figure 6 illustrates the finite source size effect where we have modelled the source with a radius of $30 R_\odot$ and a lens midway between the Sun and the source. The effect is quite dramatic. In comparison, the effect is negligible for an observer on the Earth. Note that the peak of the light curve depends on the dimensionless parameter $u_s = x/(1 - x) \, R_\odot / \hat{r}_E$. So the peak can be higher if the lens is closer or the stellar radius turns out to be smaller than our estimate, and vice versa. If the finite source size effect is indeed observed, this would allow the first complete determination of the lens configuration, including the lens distance, mass and transverse velocities by combining $t_E, \hat{r}_E$, and $u_s$. For this step, we assume that the source distance and stellar radius can be reasonably estimated as above. In this regard, spectroscopic observations of this star would be very helpful for determining the stellar parameters more precisely.

In conclusion the main aim of this paper is to strongly encourage observational efforts towards the determination of the physical parameters of OGLE-2000-BUL-43.

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Table 1
The best standard model (first row) and the best parallax model with blending (second row) for OGLE-2000-BUL-43.

|   | $t_0$  | $t_E$ (day) | $w_0$  | $m_I,0$ | $\theta$ | $\bar{r}_E$ (AU) | $f$  | $\chi^2$ |
|---|--------|-------------|--------|---------|----------|-------------------|------|---------|
| S | 1898.7 ± 0.1  | 169.6 ± 0.3 | +0.0 ± 0.002  | 13.5366 ± 0.0003 | —         | —                | —    | 10768.7 |
| P | 1893.4 ± 0.9  | 156.4 ± 3.9 | 0.27 ± 0.01  | 13.5406 ± 0.0004 | 3.024 ± 0.005 | 3.62 ± 0.16     | 0.91 ± 0.05 | 374.7  |
Fig. 1.— Finding chart for the OGLE-2000-BUL-43 microlensing event. The size of I-band subframe is $120'' \times 120''$; North is up and East to the left.
Fig. 2.— I-band light curve for the microlensing event OGLE-2000-BUL-43. The magnitude scale is shown on the left y-axis, while the linear magnification is shown on the right y-axis. The dotted line is the standard model while the solid line is a model that takes into account the parallax effect and blending. The vertical dashed line marks Jan. 1, 2001, 0UT. The three insets show the data points for the 1997, 1998 and 1999 seasons, respectively.
Fig. 3.— Distribution of residuals with respect to the model for measurements with the DIA pipeline (solid line) and DoPhot (dotted line). Width of the bin is 0.005 mag. Sigmas of fitted Gaussians are 0.0055 and 0.0262 respectively for DIA and DoPhot results. Additional dashed vertical lines indicate the largest differences between the classical single point microlensing model and the parallax fit.
Fig. 4.— Color-magnitude diagram of the BUL\textsc{Sc7} field. Only about 10\% of field stars are plotted by tiny dots. Position of OGLE-2000-BUL-43 event is marked by cross in the circle.

OGLE-2000-BUL-43

\begin{align*}
V_s &= 15.65, \quad I_s = 13.54, \quad (V-I)_s = 2.11
\end{align*}
Fig. 5.— Illumination patterns for OGLE-2000-BUL-43 in the heliocentric ecliptic coordinates on Jan. 1, 2001, 0UT. The +x-axis points from the Sun toward the Earth on the day of Vernal Equinox. The two solid elliptical curves are the iso-magnification contours with magnification 1.342 and 4, respectively. The three dotted circles are the orbits of the Earth, Jupiter and Saturn, respectively. The solid filled dots on the Earth, Jupiter and Saturn orbits indicate their positions on Jan. 1, 2001, while the open dots indicate their positions every half a year in the future. The straight line indicates the lens trajectory and the dot symbols have the same meaning as those on the planetary orbits. The directions of motions are indicated by arrows. Notice that the whole illumination pattern (iso-magnification contours) comoves with the lens.
Fig. 6.—Light curve for OGLE-2000-BUL-43 as seen by an observer on the Jupiter. Notice that it reaches a much higher peak around Jan. 31, 2001 than that on the Earth. The vertical dashed line marks Jan. 1, 2001, 0UT (corresponding to the filled dots in Figure 5). The magnitude scale is shown on the left $y$-axis, while the linear magnification is shown on the right $y$-axis. The dotted line shows the magnification for a point source while the solid line illustrates the finite source size effect. The inset shows the light curve close to the peak of the light curve.
Fig. 7.— Illumination patterns for OGLE-2000-BUL-43 in the heliocentric ecliptic coordinates on Jan. 31, 2001, 0UT. The notations are similar in Figure 5. The filled dots correspond to $t = 1840.5$ while the open dots are separated by 15 days. The contours correspond to magnifications of 5, 20 and 40 (from outer to inner), respectively. The two dashed lines bracket roughly the region that the finite source size effect can be observed.