The Extreme Microlensing Event OGLE-2007-BLG-224: Terrestrial Parallax Observation of a Thick-Disk Brown Dwarf

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ABSTRACT

Parallax is the most fundamental technique to measure distances to astronomical objects. Although terrestrial parallax was pioneered over 2000 years ago by Hipparchus (ca. 140 B.C.E.) to measure the distance to the Moon, the baseline of the Earth is so small that terrestrial parallax can generally only be applied to objects in the Solar System. However, there exists a class of extreme gravitational microlensing events in which the effects of terrestrial parallax can be readily detected and so permit the measurement of the distance, mass, and transverse velocity of the lens. Here we report observations of the first such extreme microlensing event OGLE-2007-BLG-224, from which we infer that the lens is a brown dwarf of mass $M = 0.056 \pm 0.004\, M_{\odot}$, with a distance of $525 \pm 40\,\mathrm{pc}$ and a transverse velocity of $113 \pm 21\,\mathrm{km\,s^{-1}}$. The velocity places the lens in the thick disk, making this the lowest-mass thick-disk brown dwarf detected so far. Follow-up observations may allow one to observe the light from the brown dwarf itself, thus serving as an important constraint for evolutionary models of these objects and potentially opening a new window on sub-stellar objects. The low a priori probability of detecting a thick-disk brown dwarf in this event, when

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combined with additional evidence from other observations, suggests that old substellar objects may be more common than previously assumed.

Subject headings: astrometry – gravitational lensing –stars: brown dwarfs

By several measures OGLE-2007-BLG-224 was the most extreme microlensing event (EME) ever observed, having a substantially higher magnification, shorter-duration peak, and faster angular speed across the sky than any previous well-observed event. These extreme features suggest an extreme lens. Fortunately, the observations themselves had extreme characteristics, and these permit one to test the nature of the lens.

OGLE-2007-BLG-224 was announced as a probable microlensing event by the OGLE collaboration (Udalski 2003) on 9 May 2007 and independently by the MOA collaboration (Bond et al. 2002) on 12 May as MOA-2007-BLG-163. At discovery, it was already recognized to be quite short, Einstein timescale $t_{\rm E} \sim 7\,$days, and was consistent with peaking at high magnification, although with very low probability of doing so. Such high-mag events (typically defined as $A_{\rm max} > 100$) are extremely sensitive to planets, and hence planet-detection groups attempt to predict these rare events so as to intensively monitor them over their peak. This is notoriously difficult, especially for short events, because so little information is available before peak. Indeed, four of the five high-mag events that have to date yielded planet detections had much longer-than-average Einstein timescales, $t_{\rm E} > 40\,$days (Udalski et al. 2005; Gould et al. 2006; Gaudi et al. 2008a; Bennett et al. 2008; Dong et al. 2009). Nevertheless, 20 hours before peak, OGLE issued an alert calling this a "possible high-magnification event", and 10 hours later, by combining OGLE and MOA data, including points from MOA just 12 hours before peak, the μFUN collaboration was able to predict $A_{\rm max} > 50$ and on this basis issued a general alert advocating intensive observations.

As a result, on the night of the peak, the μFUN Bronberg 0.35m telescope (South Africa) obtained 754 unfiltered images over 6.5 hours ending at UT 03:43 just 10 minutes before peak, during which the magnified flux increased by a factor 38. The μFUN SMARTS 1.3 m telescope (Chile) obtained a total of 304 images (52 in I band, 8 in V, and 244 in H) over 5.5 hours beginning 38 minutes before peak; and the OGLE 1.3m Warsaw telescope obtained 62 images (57 in I and 5 in V) over 6.9 hours beginning 25 minutes before peak. The RoboNet 2m Liverpool telescope obtained 8 R images whose number and timing were determined by an automated program (Snodgrass et al. 2008; Tsapras et al. 2009) that queries several photometry databases and attempts to optimize observations. Critically, two of these observations were about 35 minutes before peak and two others were 25 minutes after peak.

Additional observations were obtained by the MOA 1.8m telescope (New Zealand), the

μFUN 0.4m Auckland, 0.35m Farm Cove, and 0.4m Vintage Lane telescopes (New Zealand), the μFUN 1.0m Mt. Lemon telescope (Arizona), the PLANET 1.0m Canopus (Tasmania), 0.6m (Perth), 1.5m Boyden (South Africa) and 1.54m Danish (Chile) telescopes, as well as the RoboNet Faulkes North 2m (Hawaii), and Faulkes South 2m (New South Wales) telescopes. These observations helped in the determinations of the event's overall parameters, but not in the characterization of the peak, which is the central focus of this *Letter*.

Normally, microlensing events yield only one physical characteristic parameter, the Einstein timescale $t_{\rm E}$, which is a degenerate combination of three physical parameters of the system, i.e., the lens mass M, the lens-source relative proper motion in the Earth frame, $\boldsymbol{\mu}_{\rm geo}$, and the lens-source relative parallax $\pi_{\rm rel} = {\rm AU}/D_l - {\rm AU}/D_s$,

$$t_{\rm E} = \frac{\theta_{\rm E}}{\mu_{\rm geo}}; \quad \theta_{\rm E} = \frac{\pi_{\rm rel}}{\pi_{\rm E}}; \quad \pi_{\rm E}^2 = \frac{\pi_{\rm rel}}{\kappa M}, \tag{1}$$

where D_l and D_s are the lens and source distances and $\kappa = 4G/c^2{\rm AU} \sim 8.1\,{\rm mas}\,M_\odot^{-1}$. Here, $\pi_{\rm E} = {\rm AU}/\tilde{r}_{\rm E}$ is the "microlens parallax", the ratio of the radius of the Earth's orbit to the Einstein radius projected on the observer plane, $\tilde{r}_{\rm E}$. See Figure 1 of Gould 2000 for a geometric derivation of the relations between $(\pi_{\rm E}, \theta_{\rm E})$ and $(M, \pi_{\rm rel})$.

Hence, if the lens is unseen, its mass and distance can be determined only by measuring both $\theta_{\rm E}$ and $\pi_{\rm E}$ (Gould 1992). It is quite rare that either of these parameters can be measured, and only three times (out of $>$ 4000 events) have both been well-measured without seeing the lens itself (An et al. 2002; Jaroszynski et al. 2005; Kubas et al. 2005). However, as pointed out more than a decade ago, EMEs present a unique opportunity to measure both parameters (Gould 1997).

First, during an EME peak, the lens is very likely to transit the source, giving rise to distinctive "finite-source" effects that yield $\rho = \theta_*/\theta_{\rm E}$, the ratio of the source radius to the Einstein radius. At high magnification, $A = 1/u$, where u is the source-lens separation in units of $\theta_{\rm E}$. Since typically $\theta_{\rm E} \sim 0.5\,{\rm mas}$ and $\theta_* \sim 0.5\,\mu{\rm as}$, such effects are expected for $A_{\rm max} \gtrsim 1000$. In the present case, we find that the lens transited the source with an impact parameter of $\sim \theta_*/3$, which permits a very accurate determination of $\rho = 8.50 \pm 0.16 \times 10^{-4}$. We measure the source radius θ_* by extending the method of (Yoo et al. 2004), to three bands, VIH (Bennett et al. 2009). We obtain calibrated VI data from OGLE-II, and calibrated H data by aligning SMARTS H-band to 2MASS (Skrutskie et al. 2006). We measure the position of the clump and the source in 3 bands $(V, I, H)_{\rm cl} = (17.32, 15.28, 13.33) \pm (0.1, 0.1, 0.1)$, $(V, I, H)_{\rm s} = (20.58, 18.91, 17.50) \pm (0.02, 0.02, 0.02)$, We adopt $(M_V, M_I, M_H) = (0.79, -0.25, -1.41) \pm (0.08, 0.05, 0.04)$ based Alves et al. (2002) adjusted for the α-enhanced environment of the bulge (Salaris & Girardi 2002). We perform a Monte Carlo Markov Chain (MCMC) over a model with 4 parameters, a Cardelli et al.

(1989) extinction law characterized by R_V, the mean visual extinction toward the clump $A_{V,\mathrm{cl}}$, the mean distance to the clump, R_0', and the extinction difference between the source and the clump δA_V. We assume (based on experience with high-resolution spectra of bulge dwarfs) that $\delta A_V = 0 \pm 0.1$, and we demand that the resulting $(V-I)_{0,\mathrm{s}}$ be consistent with that predicted by Bessell & Brett (1988) from $(V-H)_{0,\mathrm{s}}$, with an error of 0.03 mag. We then use the Kervella et al. (2004) $(V-H)$ color/surface-brightness relation to derive $\theta_* = 0.77 \pm 0.03\,\mu$as, where the error also accounts for uncertainty in the model of the source flux (which affects all three bands in tandem). As a check, we note that this procedure yields $R_{VI} \equiv A_V/E(V-I) = 2.01 \pm 0.10$, a typical value for the bulge, and $R_0' = 7.8 \pm 0.5\,\mathrm{kpc}$, which is also consistent with most estimates (keeping in mind that at $\ell = 2.37^\circ$, the bar is about 200 pc closer than the Galactic center).

This result implies $\theta_\mathrm{E} = \theta_*/\rho = 0.91 \pm 0.04\,\mathrm{mas}$. Combining this with the measured Einstein timescale, $t_\mathrm{E} = 6.91 \pm 0.13\,\mathrm{days}$, yields a proper motion in the Earth frame (An et al. 2002; Gould 2004) of $\mu_\mathrm{geo} = \theta_\mathrm{E}/t_\mathrm{E} = 48 \pm 2\,\mathrm{mas\,yr^{-1}}$.

Second, and more dramatically, EMEs are subject to "terrestrial parallax" effects (Hardy & Walker 1995; Holz & Wald 1996). If a microlensing event is observed from two different locations, the source-lens relative trajectory will appear different: there will be a different impact parameter u_0 and a different time of closest approach t_0. Since the projected Einstein radius $\tilde{r}_\mathrm{E} = \mathrm{AU}/\pi_\mathrm{E}$ is typically of order AU, the second observer should typically be in solar orbit to notice a significant effect, and indeed one such space-based measurement has been made (Dong et al. 2007). However, the main way that microlens parallax has been measured in the past is to take advantage of the moving platform of the Earth, but usually the event must last a large fraction of a year for this to work (Poindexter et al. 2005). For EMEs, the relevant spatial scale and timescales are reduced by a factor A_max. For example, if the projected velocity of the lens is $100\,\mathrm{km\,s^{-1}}$ in the westward direction, then t_0 will be about 80 seconds later in Chile than South Africa. Measuring the peak time of a normal microlensing event (which typically lasts $t_\mathrm{E} \sim 30\,\mathrm{days}$) to this precision is virtually impossible. But since the peaking timescale of this event is roughly the source crossing time, $t_* \equiv \rho\, t_\mathrm{E} = 8.5\,\mathrm{minutes}$, such measurements become quite practical. Indeed the event passed both South Africa and the Canaries about 1 minute earlier than Chile, with both time differences accurate to a few seconds. See Figure 1. In practice, we simultaneously account for the difference in impact parameters and peak times at all locations (An et al. 2002), as well as the Earth's orbital motion (which turns out be negligible), to measure both the microlens parallax $\pi_\mathrm{E} = 1.97 \pm 0.13$ and the direction of lens-source relative motion, $52 \pm 5^\circ$ south of west. See Figure 2. This leads to mass and relative parallax measurements

$$M = \frac{\theta_\mathrm{E}}{\kappa \pi_\mathrm{E}} = 0.056 \pm 0.004\,M_\odot \quad \pi_\mathrm{rel} = \theta_\mathrm{E}\pi_\mathrm{E} = 1.78 \pm 0.13\,\mathrm{mas} \tag{2}$$

Assuming (as is consistent with its color and flux) that the source is in the Galactic bulge ($\pi_s = 125\,\mu$as), the lens parallax and distance are $\pi_l = \pi_{\rm rel} + \pi_s = 1.90\,$mas, $D_l = {\rm AU}/\pi_s = 525 \pm 40\,$pc.

The projected velocity of the lens in the Earth frame is $\tilde{v}_{\rm geo} = \mu_{\rm geo}({\rm AU}/\pi_{\rm rel}) = 127\,{\rm km\,s^{-1}}$. To find the projected velocity in the frame of the Sun, we must remove the motion of the Earth around the Sun ($23\,{\rm km\,s^{-1}}$, almost due east). We then find $\tilde{v}_{\rm hel} = 112\,{\rm km\,s^{-1}}$ at 61° south of west. This means that the lens is moving against the direction of Galactic rotation, just 1° out of the Galactic plane (toward Galactic south). Taking account of the motion of the Sun relative to the local standard of rest (Dehnen & Binney 1998) as well as the small mean motion (and its uncertainty) of the source, we find that the lens is moving at $\tilde{v}_{\rm hel} = 113 \pm 21\,{\rm km\,s^{-1}}$ relative to the Galactic disk at its location, almost directly counter to Galactic rotation. This motion is quite consistent with the kinematics of the Galactic thick disk. (It is also consistent with Galactic halo stars, but with a probability more than 100 times smaller.) Moreover, since the inferred mass is below the threshold for burning hydrogen, the lens is almost certainly a brown dwarf. While nearby brown dwarfs of this mass have been detected (e.g., Burgasser et al. 2006; Faherty et al. 2009), these are mostly quite young and so still retain the heat generated during their collapse from a cloud of gas. The thick disk is of order 11 Gyrs old, and hence brown dwarfs have had substantial time to cool. Only those very near the hydrogen burning limit are easy to see, and then only if they are relatively nearby.

Hubble Space Telescope (HST) data were taken in V, I, J, and H bands $\Delta t_1 = 29$ days after peak when the source was magnified by a factor $A = 1.005$, and again almost exactly one year later, $\Delta t_2 = 1.08$ years. At the first epoch, the source and lens were virtually coincident, being separated by only $\mu_{\rm geo}\Delta t_1 \sim 4\,$mas, i.e., < 0.1 pixels, while at the second epoch they were separated by $\mu_{\rm hel}\Delta t_2 \sim 47\,$mas ~ 1 pixel, where $\mu_{\rm hel} = 43\,{\rm mas\,yr^{-1}}$ is the heliocentric proper motion. These observations confirm that the excess flux (above the source flux predicted from the microlensing fit) is consistent with zero, but unfortunately not with very high precision because an unrelated star lying 150 mas from the source degrades the measurements. We discuss the prospect for future observations of the lens flux below.

We now ask, given a standard Galactic model (Han & Gould 2003; Gould 2000), how likely it is that detailed information on a $t_{\rm E} = 7\,$day (but otherwise unconstrained) microlensing event toward this line of sight ($l = 2.37,\ b = -3.71$) would turn out to imply a foreground ($D_l < 4\,$kpc) thick-disk star rather than a star in the Galactic bulge? The chance is just 1/235. Hence, either we were extremely lucky to have found this object, or brown dwarfs are more common in the thick disk than our standard model for the mass function would predict. Specifically, our model assumes a relatively flat power law mass function for low-mass stars and brown dwarfs with $dN/d\log M \propto M^{-0.3}$ from $M = 0.7M_\odot$ down to $M = 0.03\,M_\odot$. This model is consistent with results from observations of nearby thin disk brown dwarfs (Pinfield et al. 2006; Metchev et al. 2008), and thus our detection would imply that brown dwarfs must be an order of magnitude more common in the thick disk than in the thin disk, in order that the a priori probability of detecting this event be $\gtrsim 10\%$. This possibility should be considered seriously, since the prevalence of old brown dwarfs is essentially unconstrained by any data, owing to their faintness.

In this light, we note that two other sets of investigators have concluded that they must have been "lucky" unless old-population brown-dwarfs are more common than generally assumed. First, Burgasser et al. (2003) discovered a halo brown dwarf, probably within 20 pc of the Sun, a volume that contains only about 7 halo stars over the entire mass range from the hydrogen-burning limit to a solar mass (Gould 2003). Yet the survey in which this object was discovered would only be sensitive to halo brown dwarfs in an extremely narrow mass range just below this limit (Burgasser 2004). Second, Gaudi et al. (2008b) analyzed a microlensing event of a nearby (1 kpc), bright ($V = 11$) source serendipitously discovered by an amateur astronomer hunting for comets, finding that it was most likely a low-mass star or brown dwarf moving at roughly $100\,\mathrm{km\,s^{-1}}$. Based on the low rate of such events (and the non-systematic character of the search), they concluded that they were "probably lucky ... but perhaps not unreasonably so" to have found this event. See also Fukui et al (2007). Finally, Faherty et al. (2009) found 14 high-velocity objects in a sample of 332 M, L, and T dwarfs, which are consistent with thick-disk or halo kinematics. Only one of these has $J - K < 0$, which would be indicative of an old, low-mass brown dwarf (Burrows et al. 2001), and with $v_{\rm tan} = 140\,\mathrm{km\,s^{-1}}$ is most likely a halo brown dwarf, but could be in the high-velocity tail of the thick-disk. At absolute magnitude $M_J = 15.9$, it must be very close to the hydrogen-burning limit $M > 0.07\,M_\odot$ if it is as old as the thick disk and halo: $\gtrsim 11$ Gyrs. As this object was found within 10 pc, it is yet another "lucky find" (compare to, e.g., Burgasser 2004). While the evidence from each of these studies is marginal, collectively they point to the need for closer investigation of the frequency of old brown dwarfs.

Brown dwarfs are very blue in $H - K$ and somewhat red in $J - H$, so H is the most favorable band to observe them. In the heliocentric frame, the lens is moving away from the source at $\mu_{\rm hel} = 43\,\mathrm{mas\,yr^{-1}}$. Hence, just 3 years after the event, the lens should be well removed from the source in Keck telescope H-band images (given its 40 mas adaptive-optics point spread function). Equivalent angular resolution with *HST* would require waiting four times longer, although it would profit from the much fainter sky as seen from space as well as its better-defined point-spread function. From Burrows et al. (2001) (Figs. 1,8,9,24) and Burrows et al. (1997) (Fig. 23) one finds that the absolute magnitude of an 11 Gyr old, $M = 0.056\,M_\odot$ brown dwarf is $M_H = 17.0$, implying $H = 25.7$ at 525 pc (assuming extinction $A_H = 0.1$). By comparison, the source is $H_s = 17.5$. In principle, the lens could be younger, in which case it would be brighter and so easier to detect. However, such high-velocity young stars are extremely rare, and there is no known mechanism for preferentially accelerating brown dwarfs to this speed.

If the lens is indeed in the thick disk, this would be a challenging but not impossible observation, and would permit a unique test of models of old brown dwarfs by comparison with an object of known mass and well-constrained age. The astrometry associated with this measurement would yield the lens-source relative proper motion $\boldsymbol{\mu}_{\rm hel}$, which would test both the *magnitude* of the microlens-based proper-motion and the *direction* of the microlens parallax, thereby confirming and refining (or contradicting) the microlens-based mass estimate (Gould et al. 2004).

Looking further ahead, the space-based *James Webb Space Telescope* (launch currently scheduled for 2013) will be able to take a spectrum of this object, thereby testing more detailed atmospheric models.

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I guess for publisher and city one could do as the ADS does and say "Published online at SISSA, Proceedings of Science"

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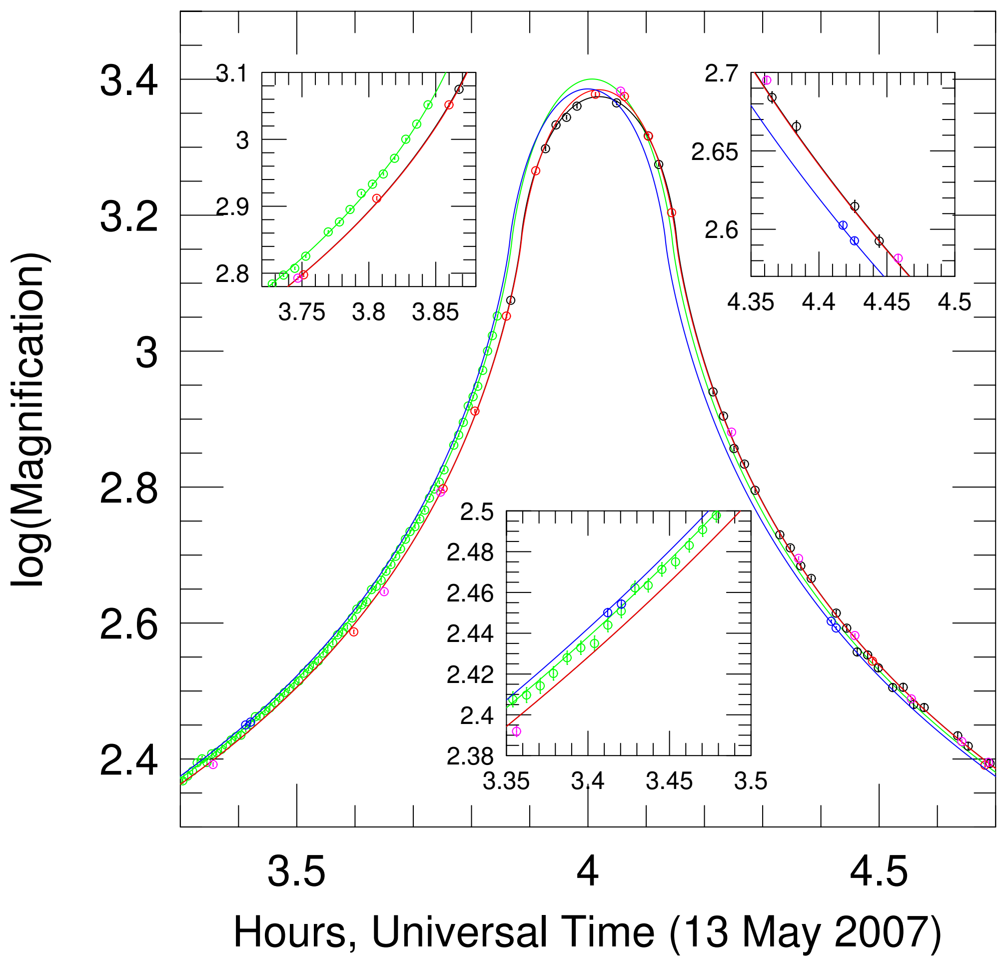

Fig. 1.— Light curve of OGLE-2007-BLG-224 during 1.4 hours closest to peak. Observatories in South Africa (Bronberg: green), Canaries (RoboNet LT: blue) and Chile (OGLE I: red, μFUN SMARTS I: magenta, μFUN SMARTS H: black) see significantly (several percent) different magnifications due to their different positions on the Earth. From these differences, one can infer that $\tilde{r}_{\rm E}$ (the projected Einstein radius) is about 10,000 Earth radii. Red and black curves (and points) deviate slightly over the peak because of different limb-darkening of the source in I and H bands.

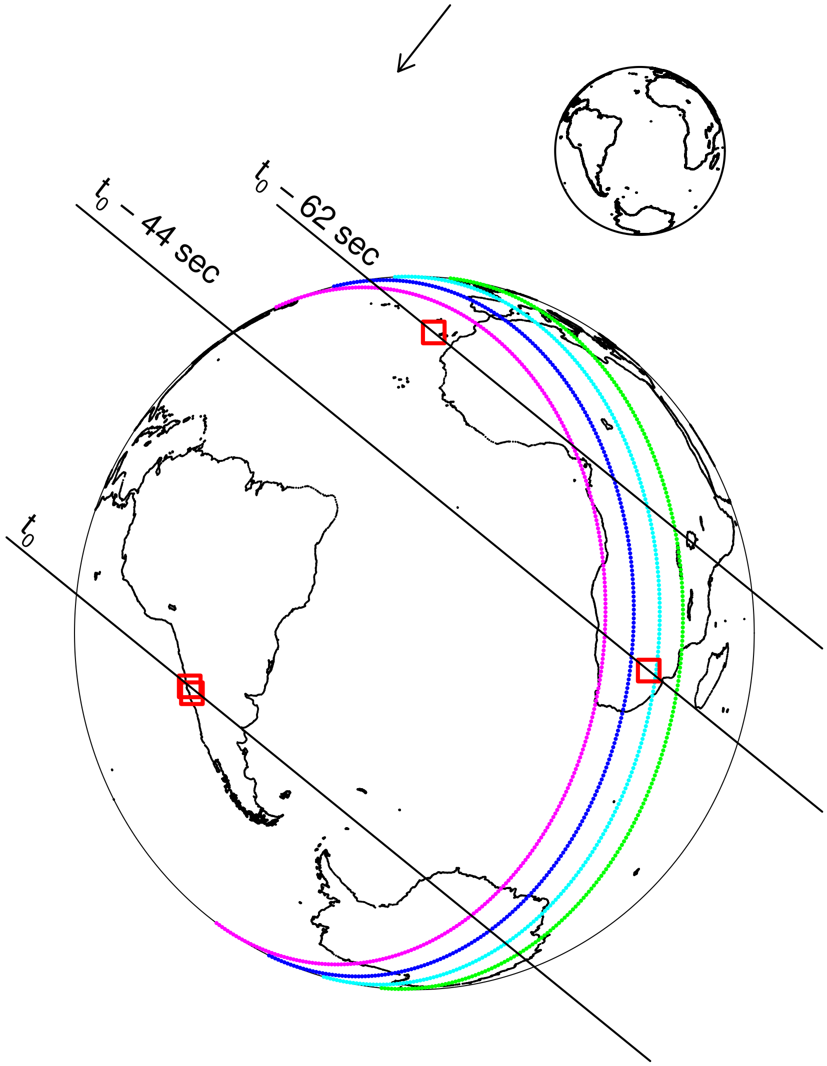

Fig. 2.— Reconstruction of microlens fly-by. Upper panel: arrow defines locus of points from which lens and source appear perfectly aligned, passing just 1 Earth diameter from the Earth's surface. Lower panel: Earth as seen from OGLE-2007-BLG-224 at the peak of the event. Red squares show the 4 observatories (in Chile, South Africa, and the Canaries) that observed near peak. Black diagonal lines show contours of constant peak time, with time offsets indicated between Chile and the other two locations. Green curve shows sunrise, while cyan, blue, and magenta curves show civil, nautical, and astronomical twilight. As shown in Fig. 1, South Africa observations stopped 10 minutes before peak due to developing daylight.