# Microlens Parallax Measurements With A Warm Spitzer

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**Abstract.** Because the Spitzer Space Telescope is in an Earth-trailing orbit, losing about 0.1 AU/yr, it is excellently located to perform microlens parallax observations toward the Magellanic Clouds (LMC/SMC) and the Galactic bulge. These yield the so-called "projected velocity" of the lens, which can distinguish statistically among different populations. A few such measurements toward the LMC/SMC would reveal the nature of the lenses being detected in this direction (dark halo objects, or ordinary LMC/SMC stars). Cool Spitzer has already made one such measurement of a (rare) bright red-clump source, but warm (presumably less oversubscribed) Spitzer could devote the extra time required to obtain microlens parallaxes for the more common, but fainter, turnoff sources. Warm Spitzer could observe bulge microlenses for 38 days per year, which would permit up to 24 microlens parallaxes per year. This would yield interesting information on the disk mass function, particularly old brown dwarfs, which at present are inaccessible by other techniques. Target-of-Opportunity (TOO) observations should be divided into RTOO/DTOO, i.e., "regular" and "disruptive" TOOs, as pioneered by the Space Interferometry Mission (SIM). LMC/SMC parallax measurements would be DTOO, but bulge measurements would be RTOO, i.e., they could be scheduled in advance, without knowing exactly which star was to be observed.

**Keywords:** Spitzer Space Telescope, infrared astronomical observations, dark matter, masses, parallaxes, distances
**PACS:** 95.85.Hp, 95.35.+d,97.10.Nf,97.10.Vm

## 1. INTRODUCTION

Microlens parallaxes measure a vector quantity, the "projected velocity" $\tilde{\mathbf{v}}$, which is the projection of the lens-source relative velocity on the plane of the observer. Another way of writing this quantity is

$$\tilde{\mathbf{v}} = \mathrm{AU}\frac{\mu_{\mathrm{rel}}}{\pi_{\mathrm{rel}}}. \tag{1}$$

where $\pi_{\mathrm{rel}}$ and $\mu_{\mathrm{rel}}$ are the lens-source relative parallax and proper motion. It is a useful quantity to measure because it depends only on the kinematic properties of the lens and source, and is independent of the mass. Once it is measured, one can also determine the "projected Einstein radius",

$$\tilde{r}_{\mathrm{E}} = \tilde{v} t_{\mathrm{E}} = \sqrt{\frac{\kappa M}{\pi_{\mathrm{rel}}}}, \tag{2}$$

where $t_{\mathrm{E}}$ is the "Einstein timescale" (which is almost always well-measured) and $\kappa \equiv 4G/c^2\mathrm{AU} = 8.1\,\mathrm{mas}/M_\odot$.

Hence, an ensemble microlens parallax measurements can distinguish statistically between different kinematic populations.

## 2. MICROLENS PARALLAX SCIENCE WITH A WARM SPITZER

Microlensing parallax measurements are feasible with Spitzer toward two classes of targets, the Large and Small Magellanic Clouds (LMC and SMC) and the Galactic bulge. The science cases and technical challenges are substantially different for the two classes.

### 2.1. Science Toward the LMC/SMC

The nature of the microlensing events detected toward the Magellanic Clouds by the MACHO (Alcock et al. [1]) and EROS (Tisserand et al. [2]) collaborations is unknown. They are definitely too infrequent to make up most of the dark matter, but could make up of order 20%. The basic problem is that, while a few of the lenses have special properties that allow their distances to be determined, for most lenses it is not known whether they are in the Milky Way (MW) halo, the MW disk, or in the Clouds themselves. While it would be tempting to use the lenses with known locations to address this question, actually the very properties that allow their distances to be measured predispose them to be in the Clouds or the MW, so they do not constitute a fair sample. It would be better to find a way to choose “typical" events, not selected by any characteristic, and determine their position.

Spitzer has already been used to measure the microlens parallax of one lens. Dong et al. [3] found that its projected velocity was $\tilde{v} \sim 230\,\mathrm{km\,s^{-1}}$, which is typical of halo lenses, but much bigger than expected for MW disk lenses and much smaller than expected for SMC lenses. However, they also found that (with no priors on the location or properties of the lens) that it could be in the SMC with 5% probability. Thus, to draw rigorous scientific conclusions, it will be necessary to obtain parallaxes for at least 3, and more comfortably 5, such events.

### 2.2. Science Toward the Galactic Bulge

Han and Gould [4] conducted a systematic analysis of what could be learned about lenses observed toward the bulge by obtaining parallaxes for an ensemble of them. They found that such parallaxes greatly enhance microlensing as a probe of the stellar mass function. For example, comparing the precision of mass estimates (for lenses assumed to be in the disk in both cases), they found that without parallaxes the masses could be individually “measured" with a $1\,\sigma$ precision of 0.6 dex (so, essentially no measurement) whereas with parallaxes, the uncertainty was reduced to 0.2 dex.

Of particular interest would be to measure the frequency of disk brown dwarfs (BDs). Of course, BDs can be directly detected, but only while they are young, so that inferences about their global frequency depend sensitively on both their history of formation and their assumed cooling properties. It would be nice to constrain their frequency based solely on their mass.

The main characteristic of disk BDs from a parallax standpoint is that they have small $\tilde{r}_{\rm E}$ (see eq. [2]). For example, a BD with $M = 0.03\,M_\odot$ and distance $D_l = 3\,$kpc would have $\tilde{r}_{\rm E} = 1.1\,$AU. In order for an M dwarf with mass $M = 0.08\,M_\odot$ to produce the same $\tilde{r}_{\rm E}$ would require a distance $D_l = 1.5\,$kpc. This is much less likely, but of course not impossible. So an ensemble of measurements would be needed to estimate to estimate the BD frequency. In fact, as I will discuss in the § 3.2, parallax measurements are actually easier for lenses with smaller $\tilde{r}_{\rm E}$ (up to a point). So Spitzer is well-placed to probe this key regime.

## 3. TECHNICAL CHALLENGES

The technical challenges in the two directions differ significantly, although they are related.

### 3.1. Technical Challenges Toward the Clouds

As mentioned, there is already one Spitzer microlens parallax toward the Clouds, which is a proof of concept. However, the source was an $I = 18$ clump giant (i.e., quite cool, so large $I - L$), which is what permitted excellent photometry with just 2 hours of integration time in each of the four measurements required. Such microlensing sources toward the Clouds are extremely rare (this was the only one detected so far during the entire Spitzer mission). To obtain the 3–5 events that are needed for the science goal, requires acceptance of more typical turnoff stars, which are both fainter and bluer, and hence demand integration times that are 10–20 times longer. Such integrations were prohibitive for cold Spitzer but might be possible for warm Spitzer when the observatory is under less severe demand. If we imagine an average of 60 hours per event for 4 events, this would take about 250 hours over 4 years. Note that the individual exposures cannot be made any longer than the 27 second exposures for the clump giant because of artifacts from very bright stars.

### 3.2. Technical Challenges Toward the Bulge

Here there are many challenges. First, because the bulge is near the ecliptic, it can only be observed for two 38-day periods per year (in late spring and late autumn). Moreover, the autumn window is almost useless for microlensing because no events can be discovered then from the ground. Second, in contrast to the Clouds, a large number of events must be monitored to obtain scientifically interesting results, close to 50 and preferably 100. Third, there are technical challenges related to reconciling ground-based and Spitzer photometry. This is a classic problem first discussed by Gould [5]. Basically, unlike trigonometric parallax, microlens parallax is actually a vector, $\pi_{\rm E}$, which is related to observations by

$$\pi_{\rm E} = \frac{\rm AU}{d_{\rm proj}}\left(\frac{\Delta t_0}{t_{\rm E}}, \Delta u_0\right) \tag{3}$$

where $\Delta t_0$ is the measured difference in times of peak of the event as seen from Spitzer and the ground, $\Delta u_0$ is the measured difference in the impact parameter, and $d_{\rm proj}$ is the magnitude of the Earth-Spitzer separation vector projected onto the plane of the sky. The problem is that while $\Delta t_0$ can be robustly measured (because the time of the peak can be read directly from the lightcurve), $u_0$ from each observatory is much harder to measure because it is a fit parameter that is partially degenerate with the amount of blended light. Gould [5] showed this degeneracy could be strongly constrained by arranging for the space and ground observatories to have identical cameras (and so identical blending) but that is obviously impossible for Spitzer observations. Dong et al. [3] evaded this problem by making Spitzer responsible only for measuring the first component of $\pi_{\rm E}$: the events toward the Clouds are long enough that the acceleration of the Earth toward the Sun (roughly perpendicular to Spitzer) allowed ground-based measurement of the other component. However, most events toward the Galactic bulge are too short to make this trick work.

In order to understand whether the first two challenges can be overcome, I plotted (not shown), all 90 OGLE events that peaked during a random 38-day period in Spring 2007, with events plotted in red before they were alerted and in black afterward. Events must be alerted before peak or it is impossible to measure $t_0$ from Spitzer. The diagram proved to be quite a mess, but much of this mess is caused by 24 events that were alerted after peak because they are so faint. The remaining 66 events are shown in Figure 1. Based on experience with Spitzer observations of the SMC event, it should be possible to obtain better than 1% photometry in one hour exposures of events that reach $I < 17$. (The bulge sources are intrinsically bluer than the SMC clump giant, but the fields are heavily reddened, so the *observed* $I - L$ colors are similar.) There are 24 such events. Hence, over 5 years, a sample of 120 events could yield measured parallaxes.

Before addressing the challenge of aligning the photometry of the two observatories, one should take note of the bottom panel in Figure 1. It shows the Earth-Spitzer separation projected onto the bulge, during each of the 5 38-day intervals of the Warm Spitzer Mission, red for the first year and blue for the last. The average value is about 0.6 AU, about 2.5 times the leverage available for the SMC event (Dong et al. [3]). This is important because, until the projected separation gets to be the same order as $\tilde{r}_{\rm E}$, the signal-to-noise ratio of the measurement scales directly as the projected separation.

A possible approach to aligning the ground and Spitzer photometry would be to obtain $L$ band images during the event from the ground with a high-resolution, large aperture telescope. Such measurements would yield an accurate $I - L_{\rm ground}$ color, independent of blending. While $L_{\rm ground}$ is certainly not identical to Spitzer $3.6\,\mu$m, it should be possible to use this color, together with the colors of other stars in the image, to align the two photometry systems based on stars of similar color. Only empirical testing will determine whether this is a practical method. One potential problem with this approach is that there may not be enough bright bluish stars to perform the alignment for the (typically bluish turnoff) stars that dominate the event rate. In this case, one might be

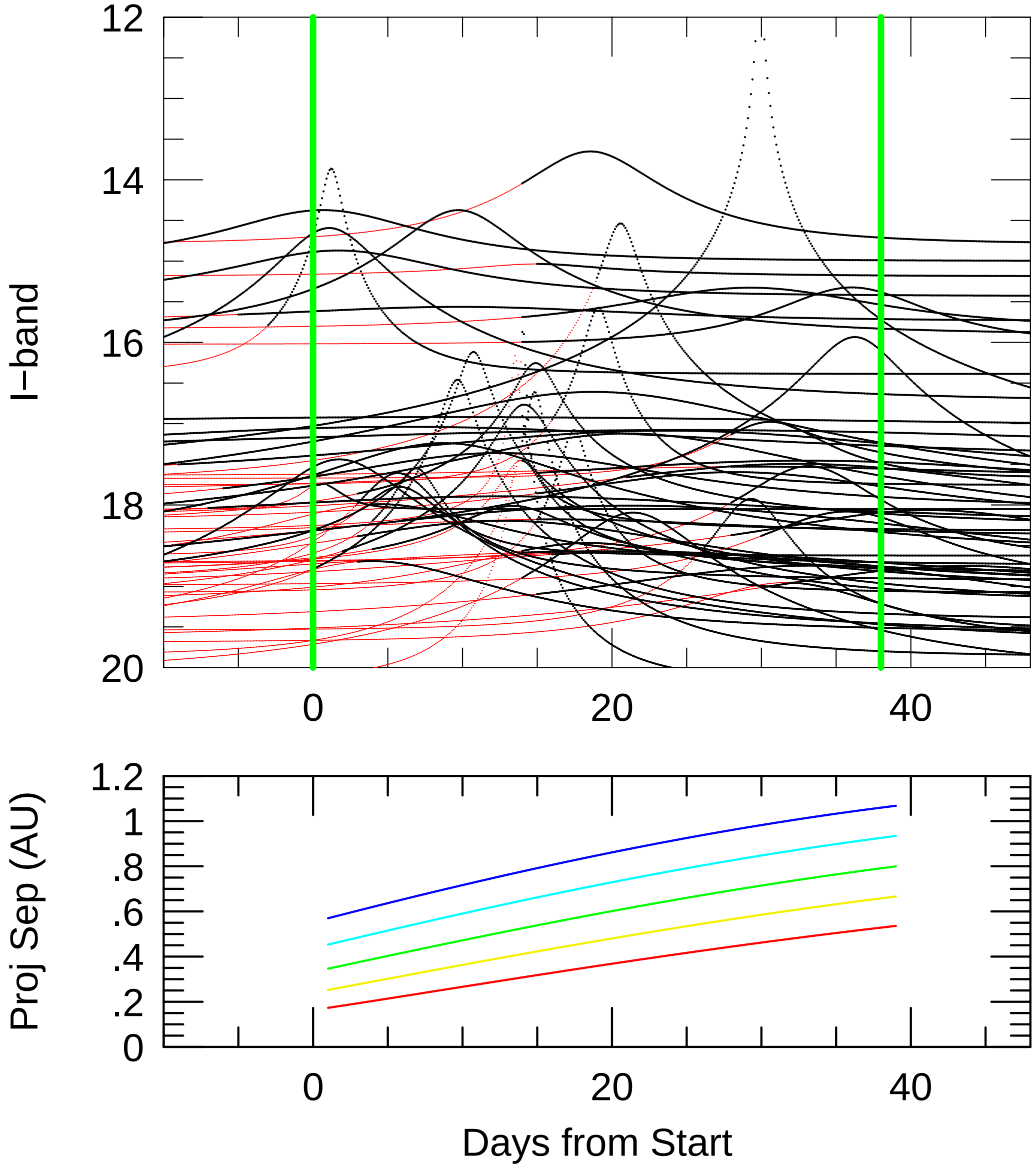


**FIGURE 1.** Upper Panel: Light curve trajectories of all 66 events discovered before peak by the OGLE collaboration (Udalski et al. [6]) during an arbitrarily chosen 38-day period beginning 1 April 2007. Thirty-eight day interval is delineated by the vertical lines. Light curves are in red prior to discovery of event and in black afterward. Lower Panel: Earth-Spitzer separation (projected onto the plane of the sky toward the Galactic bulge) as a function of time for each of the five 38-day intervals that warm Spitzer will be able to observe the bulge. Red to blue corresponds to 2009 to 2013.

forced to stick with the brighter stars, which comprise 7 stars in the interval shown in Fig. 1.

Even if it proves difficult to measure $\Delta u_0$ very accurately, it is important to point out that for one of the most interesting applications, the BD mass function, $\Delta u_0$ does not have to be measured with great precision. With typical $\tilde{r}_E < 2\,\mathrm{AU}$ and $d_{\rm proj} \sim 0.6\,\mathrm{AU}$, measurements of $\Delta u_0$ accurate to 0.1 would be quite adequate.

## 3.3. RToO/DToO

Finally, there is the question of the practical organization of bulge observations. Target-of-Opportunity (ToO) observations are notoriously disruptive, and the Warm Spitzer Mission is likely to have a lower level of staff support to deal with these disruptions than the cold mission does.

However, given the very large number of observations required during each 38-day observing “season", it should be possible apply the concept [originally developed for the Space Interferometry Mission (SIM)] of a “Regular ToO" or RToO (as opposed to a “Disruptive ToO" or DToO). For an RToO, one plans in advance to make observations of the bulge for a designated set of times, but without specifying exactly what the targets are. Then a day or so before the observations, instructions are uploaded to the spacecraft specifying the targets.

If it really proves possible to measure 24 targets, and each one requires 7 1-hr measurements (plus 1 baseline measurement that can be done at leisure during the autumn 38-day interval), then this amounts to 168 hours of observing over 38 days, or about 18% of observing time during this interval. All of these observations could be scheduled in advance, without knowing what the targets were.

## ACKNOWLEDGMENTS

This work was supported by NASA grant 1277721 issued by JPL/Caltech.

## REFERENCES

1. Alcock, C. et al. 2000, ApJ, 542, 281
2. Tisserand, P. et al. 2007, A&A, 469, 387
3. Dong, S. 2007, ApJ, 664, 862
4. Han, C. and Gould, A. 1995 ApJ, 447, 53
5. Gould, A. 1995, ApJ, 441, L21
6. Udalski, A., et al. 1994, Acta Astron., 44, 227