Combining Spitzer Parallax and Keck II Adaptive Optics Imaging to Measure the Mass of a Solar-like Star Orbiting a Cold Gaseous Planet Discovered by Microlensing

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Abstract

To obtain accurate mass measurements for cold planets discovered by microlensing, it is usually necessary to combine light curve modeling with at least two lens mass–distance relations. The physical parameters of the planetary system OGLE-2014-BLG-0124L have been constrained thanks to accurate parallax effect between ground-based and simultaneous Spitzer observations. Here, we resolved the source–lens star from sub-arcsecond blends in H-band using adaptive optics (AO) observations with NIRC2 mounted on Keck II telescope. We identify additional flux, coincident with the source to within 160 mas. We estimate the potential contributions to this blended light (chance-aligned star, additional companion to the lens or to the source) and find that 85% of the NIR flux is due to the lens star at $H_L = 16.63 \pm 0.06$ and $K_L = 16.44 \pm 0.06$. We combined the parallax constraint and the AO constraint to derive the physical parameters of the system. The lensing system is composed of a mid-late type G main sequence star of $M_1 = 0.9 \pm 0.05$ $M_\odot$ located at $D_L = 3.5 \pm 0.2$ kpc in the Galactic disk. Taking the mass ratio and projected separation from the original study leads to a planet of $M_p = 0.65 \pm 0.044$ $M_{\text{Jupiter}}$ at 3.48 $\pm$ 0.22 au. Excellent parallax measurements from simultaneous ground-space observations have been obtained on the microlensing event OGLE-2014-BLG-0124, but it is only when they are combined with ~30 minutes of Keck II AO observations that the physical parameters of the host star are well measured.

Key words: gravitational lensing: micro – planetary systems – planets and satellites: detection

1. Mass–Distance Relations for Microlensing

Gravitational microlensing is unique in its sensitivity to exoplanets down to Earth mass beyond the snow line (Mao & Paczynski 1991; Gould & Loeb 1992), where the core accretion theory predicts that the most massive planets will form. However, the major limitation of most of the 51 exoplanetary microlensing analyses published to date has been the relatively low precision measurements of physical parameters of the system, owing to uncertainty of the host star mass and its distance. By contrast, the relative physical parameters (mass ratio, projected separation relative to the angular Einstein ring radius) are usually known with high precision. In the vast majority of microlensing events, the Einstein ring radius crossing time $t_\text{E}$ is the only measurable parameter constraining the lens mass, lens distance, and relative lens-source proper motion $\mu_\text{rel}$, which are therefore degenerate. For binary microlensing events, it is possible to accurately measure the mass ratio $q$ and the projected separation $d$ in units of Einstein ring radius. The source star often transits the caustic, providing the source radius crossing time $t_s$. Moreover, the angular radius of the source star $\theta_s$ can be estimated from the surface brightness relation (Kervella et al. 2004; Boyajian et al. 2013, 2014), so the measurement of $t_s$ yields the angular Einstein radius, $\theta_E = \theta_s / t_s$.

These constraints lead to a mass–distance relation between lens mass $M_L$ at distance $D_L$, with the form

$$M_L = \sqrt{\frac{\theta_E^2}{\kappa \, \pi_\text{rel}}}$$

where $\pi_\text{rel} = (au) (D_S - D_L) / (D_S D_L)$ and $\kappa = 8.144$ mas $M_\odot^{-1}$.

There is also a relation between the parallax $\pi_E$ and the mass,

$$M_L = \sqrt{\frac{\theta_E^2}{\kappa \, \pi_E}}.$$
parallax $\pi_E$ but unknown $\theta_E$:

$$M_L = \pi_{\text{rel}}/(\kappa \pi_E^2)$$

(3)

An independent mass–distance relation can be applied if the flux from the lens system can be reliably measured and compared to stellar models. Using high angular resolution observations with Keck II, SUBARU, or HST, it is possible to separate the contributions of the source and lens stars from blended stars at the sub-arcsecond level. We can then measure the lens apparent magnitude $m_L(\lambda)$ and combine it with isochrones (e.g., Bertelli et al. 2008) to get another mass–distance relation:

$$m_L(\lambda) = 10 + 5 \log(D_L/1 \text{ kpc}) + A_L(\lambda) + M_{\text{isochrone}}(\lambda, M_L, \text{age, [Fe/H]})$$

(4)

where $M_{\text{isochrone}}$ is the predicted absolute magnitude of the lens assuming a given mass, age, and metallicity, and $A_L(\lambda)$ is the wavelength-dependent interstellar extinction along the line of sight to the lens.

In practice, the parallax vector is often not well constrained and there is a degeneracy with orbital motion, while the Einstein ring radius is usually known to about 10%. Therefore, it is quite common to combine the mass–distance relations from adaptive optics (Equation (4)) and $\theta_E$ (Equation (2)) to measure the masses. This has been done on a number of planetary microlensing events (Janczak et al. 2010; Kubas et al. 2012; Batista et al. 2014, 2015; Bennett et al. 2015). In the favorable cases, it is possible to constrain the physical parameters of the system to within $\approx 5\%$. Recently, Koshimoto et al. (2017a) presented the discovery of a sub Saturn-mass planet and estimated the mass by combining parallax measurements (Equation (3)) and adaptive optics measurement, without a good measurement of $\theta_E$. In this particular case, the accuracy of the parallax is the limiting factor determining the accuracy of the derived physical parameters. This is often the case for ground-based measurements, where only the parallax component parallel to the Earth acceleration is well measured, while the other is uncertain.

In order to overcome this limitation, a natural way forward is to obtain accurate parallaxes, by making simultaneous ground and space observations, as proposed first by Refsdal (1966) and further developed by Gould (1992). In contrast with observations from the ground alone, both components of the parallax vector could be well constrained. Three observing campaigns of simultaneous ground-based and Spitzer observations were completed in 2014–2016 (Yee et al. 2015a, 2015b; Calchi Novati et al. 2015).

2. The Planetary System OGLE-2014-BLG-0124

A very favorable case was OGLE-2014-BLG-0124, in which a system with a star plus planetary companion with mass ratio $q \sim 7 \times 10^{-4}$ and projected separation $d \sim 0.94$ was detected by the OGLE survey. It was observed simultaneously by a fleet of ground-based telescopes (MOA, LCOGT, Wise 1 m, MINDSTEP, and SAAO 1m), and by the Spitzer space telescope. It should be emphasized that this event was very favorable for parallax detection given its long timescale. During the ongoing microlensing event, models were circulated to characterize the nature of the event and optimize requests for complementary observations from follow-up telescopes.

Udalski et al. (2015) presented the analysis of OGLE and Spitzer data. OGLE captured the overall geometry of the microlensing light curve, a source transiting close to a resonant caustic. Although their model was ultimately based on OGLE and Spitzer data alone, it was completely consistent with the models created during the event, including data collected by the fleet of follow-up telescopes. Unfortunately, the original study failed to acknowledge this contribution from the community.

The OGLE data on its own allowed a $\pi_E$ measurement to $\pm 20\%$. The inclusion of Spitzer data improved this by a factor seven, making OGLE-2014-BLG-0124 the most precise microlensing parallax measurement to date. Unfortunately, the trajectory of the source star did not make any caustic crossings; Udalski et al. (2015) showed that $t_\text{d}$ is uncertain, which transfers into a poorly known $\theta_E$, and hence a large uncertainty on physical mass of the host star. It was also discussed by Yee (2015).

As a result, the system has two published solutions, which overlap within the errorbars. The first, for $u_0 > 0$, has an $M = 0.71 \pm 0.22 M_\odot$ star located at $4.1 \pm 0.6$ kpc in the galactic disk, orbited by a planet of $M = 0.51 \pm 0.16 M_{\text{Jupiter}}$ at $3.1 \pm 0.5$ au; The second one ($u_0 < 0$), has an $M = 0.65 \pm 0.22 M_\odot$ star located at $4.23 \pm 0.59$ kpc in the galactic disk, orbited by a planet of $M = 0.47 \pm 0.15 M_{\text{Jupiter}}$ at $2.97 \pm 0.51$ au. We remark that the microlensing parameters (mass ratio, projected separation) are very close and that the small difference in the physical parameters is coming mostly from the Bayesian modeling.

2.1. Source Star Properties

Udalski et al. (2015) fitted the source magnitude $I_S = 18.59 \pm 0.02$ with a bright blend contribution of $I_{\text{blend}} = 17.79 \pm 0.01$. They estimated the extinction to be $A_I = 1.02$, so $A_H = 0.236$ and $A_K = 0.17$, which leads to a dereddened source color of $(V-I)_{\text{der}} = 0.70$. Using the relations in Bessell & Brett (1988), we derived $(I-H)_{\text{der}} = 0.765$ and $(H-K)_{\text{der}} = 0.055$. Knowing the extinction in the different bands, we predict the source magnitudes to be $H_S = 17.04 \pm 0.05$ and $K_S = 16.985 \pm 0.05$.

A direct measurement of the near-infrared magnitude of the source+ lens therefore allows us to find the flux of the lens, and then to use Equation (4) to get a new mass–distance relation. We follow Bennett et al. (2015) and Beaulieu et al. (2016) to estimate the extinction toward the lens. We adopt as a scale height of the dust toward the galactic bulge $\tau_{\text{dust}} = (0.120 \text{kpc})/\sin(b)$, where $b = -25\degree 9167$ is the galactic latitude. Then we write the lens extinction $A_{H_S}$:

$$A_{H_S} = (1 - e^{-D_H/\tau_{\text{dust}}})/(1 - e^{-D_S/\tau_{\text{dust}}})A_{H_S}.$$  

(5)

2.2. VVV K-band Light Curve of OGLE-2014-BLG-0124

We extracted H and K cubes of images centered of the target collected by the 4 m VISTA telescope at Paranal during the VVV survey (Minniti et al. 2010). The data set is composed of 1 H and 312 K-band epoch. Using our standard procedure, we perform PSF photometry on all of the frames and calibrated them (Beaulieu et al. 2016; J.-B. Marquette et al. 2017, in preparation).

We use both VVV, OGLE, and Spitzer data to fit a binary-lens microlensing model using Markov Chain Monte Carlo, in order to double-check the initial study by Udalski et al. (2015) and to derive an estimate of the $K_S$ band calibrated source flux.
We correct for dark and flatfield using standard procedures and stack the images using Swarp from the AstraMatic suite of astronomy tools (Bertin 2010). We cross identify the VVV and Keck II sources and estimate the calibration constant. We estimate the uncertainty on the zeropoint to be 0.008 mag in H and 0.01 in K. We apply this zeropoint to the Keck II catalogs.

We identify the source+_lens star at the position marked on Figure 2. It has several blends at the ~2 arcsec level. The total magnitude is $H_{\text{VVV}} = 15.75 \pm 0.07$ and $K_{\text{VVV}} = 15.66 \pm 0.10$ in the VVV images.

At the predicted position of the source, we measure $H_{\text{Keck}} = 15.95 \pm 0.04$ and $K_{\text{Keck}} = 15.79 \pm 0.03$. The PSF is slightly elongated due to the observing conditions; the ellipticity is identical to the PSF of nearby stars. As the source has $H_S = 17.04 \pm 0.05$ and $K_S = 16.93 \pm 0.03$, we estimate the blended light to be $H_{\text{Blend}} = 16.45 \pm 0.06$ and $K_{\text{Blend}} = 16.26 \pm 0.05$.

### 3. Lens Star Properties

We detected blended light aligned with the source to an order better than the 160 milliarcsecond PSF full-width at half-maximum, so we must estimate if it is likely to be the lens star alone, or has contributions from:

1. the lens;
2. an ambient star (aligned with source and lens not associated with either);
3. a companion to the lens; and/or
4. a companion to the source.

We decided to compute the contribution to the blended light using two different methods and compare them.

#### 3.1. Estimating Contaminants, Batista et al.’s Approach

We follow the Bayesian analysis described in V. Batista et al. 2018 in preparation. First, we calculate the probability for
an unrelated star in the magnitude range $H = 15-21$ to be aligned by chance with the lens and the source. We assume that stars with a separation larger than $0.8 \times \text{FWHM}_{\text{Keck}} = 130$ mas would be resolved. The probability of a field star contribution to the extra NIR flux is then equal to the surface number density of stars multiplied by the area ratio between a circle of 130 mas and the entire field.

While the upper limit to the separation is observationally given by $0.8 \times \text{FWHM}_{\text{Keck}}$, the appropriate lower limits differ between a lens companion and a source companion. For a lens companion, we consider lower limits given the absence of signature from a source and a lens companion in the light curve, following the approach of Batista et al. (2014). We take a conservative lower limit to the separation by considering the upper limit on the microlensing shear that would be induced by an additional caustic,

$$\gamma = \frac{q}{s} < 10^{-3}.$$ 

For a source companion, the lower limit is given by the minimum separation for which the companion would not produce an additional perturbation in the light curve,

$$s \geq 1/4 \theta_E \sim 0.23 \text{ mas}.$$ 

The source and lens companions prior distributions of flux are calculated following the properties of binary star populations described by Duchêne & Kraus (2013, see V. Batista et al. 2017 in preparation for details). The distributions of the four potential contributors (lens, ambient star, source, or lens companion) are shown in Figure 3.

We combine the expected flux contributions from the four potentially luminous objects into 500,000 chains, weighted by their distributions and the Keck measurement. We extract a sample of the 1000 best fits and conclude that the most likely value of the lens contribution to the extra NIR flux is 85%. Figure 4 gives the posterior probability distribution of the sources of extra flux, with the inset showing the most probable contribution of each source to the detected object within a 160 mas separation.

3.2. Estimating Contaminants, Koshimoto et al.’s Approach

The same calculation has also been done following the approach of Koshimoto et al. (2017b); these authors also use the multiplicity estimates from Duchêne & Kraus (2013), but the treatment of the surface density distribution of field stars is slightly different. The two approaches also slightly differ in their a priori distributions: Koshimoto et al. (2017b) use a continuous law that is a function of the primary mass, whereas V. Batista et al. 2017 in preparation use a set of distinct laws associated to different mass bins.

Moreover, Koshimoto et al. (2017b) use a Galactic model in their calculation, while V. Batista et al. 2017 in preparation use the best-fit parameters from Udalski et al. (2015) for $M$, $D_1$, $D_2$, and $\theta_{E}$, and the OGLE calculator for $D_S$. Finally, the treatment of the Keck measurement in their Bayesian analysis slightly differs, as Koshimoto et al. (2017b) use it as a selection criteria of their flux combinations, while V. Batista et al. 2017 in preparation use it as an a priori distribution.

Nevertheless, prior and posterior distributions are very similar, and the fraction of the blended flux attributed to the lens is in agreement with the approach we adopted. The different contributions are estimated to be 79.3% for the lens, 2.4% for a chance-aligned star, 10% for a companion to the source, and 8% for a companion to the lens. This would lead to a lens less massive by $\sim 0.005 M_\odot$ than using the approach adopted in the previous paragraph. We repeat the same calculation for the K-band data and obtain very similar results.

We conclude that the lens contributes to the great majority of the excess NIR flux detected in the Keck adaptive optics images, regardless of minor variations to the calculation of contamination probabilities.

4. Discussion and Conclusions

We estimated that 85% of the blended flux is due to the lens in $H$; therefore, $H_L = 16.63 \pm 0.06$. A similar result is obtained for $K$, so $K_L = 16.44 \pm 0.06$. We present in Figure 5 the constraints on mass and distance obtained for
OGLE-2014-BLG-0124, via the three different routes summarized in Equations (2)–(4), namely: parallax, constraint on $\theta_E$, and measuring the light from the lens. First, we use the mass–distance relation from $\theta_E$ and OGLE parallax; this gives a poor constraint on mass and distance of the system. However, the parallax constraint coming from OGLE combined with Spitzer is much stronger (drawn in pink). The gray squares indicate the two solutions for $u_0 > 0$ and $u_0 < 0$ presented by (Udalski et al. 2015), combining the accurate ground-space parallax with the mass–distance relation from $\theta_E$ (blue band). The latter constraint is quite weak due to the absence of caustic crossings in the source trajectory, with the consequent uncertain fitted value of $\mu_0$.

Our solution, plotted as a black square, relies on well-determined parameters from adaptive optics measurements and Spitzer parallax and is in good agreement with the loose $\theta_E$ constraint. The lens star is an $M_L = 0.90 \pm 0.05 M_\odot$ at a distance of $D_L = 3.5 \pm 0.2$ kpc. The microlensing fit gives two solutions, for $u_0 > 0$ and $u_0 < 0$. The parallax is nevertheless very close, as we get $\Pi_E = 0.148 \pm 0.0064$ and $\Pi_E = 0.146 \pm 0.006$, which give two mass–distance relations that are overlapping. The crossing of these constraints with the mass–distance relation coming from the detection of the lens gives the same solution for the lens mass. At this mass, the lens star would be a typical mid-late type main sequence star in the disk. Age constraints are weak, but most compatible with a typical age for disk stars, in the range $\sim 4$–7 Gyr, assuming solar metallicity. Using the lens mass $M_L$, distance $D_L$, and the parallax $\Pi_E$ we can recalculate that $\theta_E(\text{calc}) = 1.03 \pm 0.06$ mas, corresponding to $3.69 \pm 0.21$ au. We then use mass ratios and projected separation presented by Udalski et al. (2015) for the $u_0 > 0$ and $u_0 < 0$ cases. The two solutions for the physical parameters are very close (mutually consistent within error bars), so we conclude that $M_p = 0.65 \pm 0.044 M_{\text{Jupiter}}$ at $3.48 \pm 0.22$ au.

This study shows the power of high angular resolution observations for constraining the host star properties in planetary microlensing events. It is also a cautionary tale showing that it is important to carefully estimate the potential contribution of source and lens companions that may potentially bias the inferred host properties if they are not accounted for. We note that for fainter lenses, these contributions will be more dramatic, like the case of MOA-2016-BLG-227 (Koshimoto et al. 2017b); a dedicated study will have to be performed in the framework of Euclid and WFIRST. Not accounting for these potential companions might lead to a bias toward higher inferred lens masses. In this case, because the lens star is bright, doing so would have resulted in a host mass $\sim 0.02 M_\odot$ larger. This will become even more important in the case of fainter source and lens stars.

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