Microlensing with Spitzer
uncover lens masses and distances by parallax measurements

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OUTLINE

- The Microlensing Parallax
  - Breaking the degeneracy in the lensing parameter space
- The *Spitzer* 2014 pilot program
  - Mass Measurement for OGLE-2014-BLG-0124L Planet
  - First Space-based Microlens Parallax Measurement of an isolated star
  - Parallax measurements of 21 Single-Lens events

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The key astrophysical issues

- Determination of the lens **mass**
  - *Planetary* events (binary lens systems)
  - Mass function for single lens systems (*not light-based*)
- Analysis of the lens **distances**
  - Measurement of Galactic distribution of planets
Microlensing event: the light curve

A single observable, the event duration, for three unknown physical parameter

Bottom line: degeneracy in the lensing parameter space

- Lens mass?
- Lens distance?
- Relative lens-source velocity?

Breaking the degeneracy?

need for a ruler in the sky

- Source plane (source angular radius): Source finite size effect ($\rho = \theta_*/\theta_E$ vs $u_0$)

- Observer plane (projection of the Einstein radius): parallax, $\pi_E$
  (need of a long baseline, $\sim AU$)

- Earth orbital motion (biased sample)
- Simultaneous observations from Earth and a satellite in solar orbit
Looking back and forward

Liebes, 1964; Refsdal, 1964: degeneracy in microlensing parameter space
Refsdal 1964: break degeneracy with microlensing parallax
(observation from solar orbit)

Paczyński, 1986

Gould, 1992: parallax from Earth solar orbit
Gould 1994: parallax from simultaneous Earth and satellite observations
Alcock et al 1995 (MACHO): first parallax measurement (Earth motion)
Han and Gould 1995: the mass spectrum from parallax
Gaudi and Gould 1997: satellite parallaxes towards the Galactic Bulge
Gould 1999: Microlens parallaxes with SIRTF

Dong et al, 2007 First space-based Microlens Parallax: Spitzer for OGLE-2005-SMC-001
Gould, 2013: Geosynchronous Microlens Parallaxes
Yee, 2013: WFIRST (if in L2 orbit) planet masses from Microlens Parallax

today:
2014 Spitzer Microlensing pilot program

Udalski, Yee, Gould et al (SCN) 2014 (submitted)
Yee, Udalski, Calchi Novati et al 2014 (submitted)
Calchi Novati et al 2014 (in preparation)
Spitzer Microlens Planets and Parallaxes

a 100 hr (38 2.6hr windows) pilot program  
PL: A. Gould, co-I: S. Carey, J. Yee (DDT #10036)

Measure of microlens parallaxes by simultaneous observations from Spitzer, at about 1 AU from Earth, of microlensing events toward the Galactic Bulge alerted and observed by the OGLE survey (~ 2000 new event/9 months in 2014)

Why (and why not) Spitzer
- Solar orbit
- 3.6 μm camera, ≈ 2'' PSF
- Short notice
  - Can only observe the Bulge for two ~38 d intervals/year
  - Rapid responses are very disruptive to mission

Observation carried out in June 2014 (HJD-245000=6814, 6850)
New protocol for «regular» ToO observations with 3-9 day turnaround (AG, JCY)
- 60 events observed (OGLE)
  - 1 planetary event
  - 4-5 binary (→ poster by W. Zhu)
  - 22 single-lens events analyzed
  - 15 (single-lens) under investigation
  - ~17 insufficient sampling

Scientific purposes
- Probe feasibility (pilot program!)
- Microlensing lens masses and distances (planetary events)
Spitzer 2014 pilot program

Typical event duration \(\sim 25\) days (shorter for bulge than for disk lenses)

the challenge: predict the evolution of the event well before peak

besides: the lightcurve from Spitzer is going to look different from that from Earth (that’s the point of parallax observations!)

The protocol biases our sample in favour of the longer duration disk lenses
First space-based microlens parallax of an isolated star
Spitzer observations of OGLE-2014-BLG-0939

Parallax measurements
and parameter space degeneracies

\[ \pi_E = \frac{AU}{D_\perp} \left( \frac{\Delta t_0}{t_E}, \Delta u_0 \right) \]

bottom line: 4 minima in \( \chi^2 \) (4 \( \pi_E \) solutions)
with 2 values for the amplitude \( \pi_E \)

Yee, Udalski, SCN et al 2014, submitted
OGLE-2014-BLG-0939 parallallax measurements from *Spitzer* a Galactic disk lens: $M = 0.23 \pm 0.07 \, M_{\odot}, \, D_l = 3.1 \pm 0.4 \, kpc$

Yee, Udalski, SCN et al 2014, submitted

\[ \pi_E \equiv \frac{\pi_{rel} \mu}{\theta_E \mu} \]

\[ \pi_{rel} = AU \left(1/D_l - 1/D_s\right) \]

\[ \widetilde{\nu}_{hel} = \widetilde{\nu}_{geo} + \nu_{\oplus\perp}, \]

\[ \widetilde{\nu}_{geo} = \frac{\pi_{E,geo} \, AU}{\pi_E^2 \, t_E} \]

\[ \mu = \frac{\widetilde{\nu}}{AU \, \pi_{rel}} \]

\[ M = \frac{\mu_{geo} \, t_E}{k \, \pi_E} = \frac{\theta_E}{k \, \pi_E} \]

*a key point: the reduced velocity, $\tilde{v}$, depends on the kinematic properties of lens and source and is independent of the lens mass*
Spitzer as Microlens Parallax Satellite: Mass measurement for the OGLE-2014-BLG-0124L Planet and its Host Star

\[ \theta_E = 0.84 \pm 0.26 \text{ mas} \quad \text{(for } M < 1.2 \, M_\odot) \]

\[ \pi_E = 0.15 \, (2.5\%) \]

\[ M_{\text{host}} \sim 0.71 \, M_\odot \]

\[ M_{\text{planet}} \sim 0.51 \, M_{\text{jup}} \]

\[ D_l \sim 4.1 \text{kpc} \]

\[ a_\perp \sim 3.16 \text{ AU} \]

Relative error \sim 30\% from that on \( \theta_E \)

Udalski, Yee, Gould et al (SCN) 2014, submitted
OGLE-2014-BLG-0124L: confirmation of (orbital motion) Earth parallax measurement \( (t_E \sim 150 \, d) \) by OGLE alone

Second ever case (over a dozen) for which this test is possible after LMC-5 (Alcock et al 2001; Gould 2004; Gould et al 2004) where however only a 1-d test was carried out.

\[ \pi_{E,N} \]

\[ \pi_{E,E} \]

\[ \Delta \pi_{E,E} \]

\[ \Delta v_{\text{hel,E}} \]

Udalski, Yee, Gould et al (SCN) 2014, submitted
Pathway to the Galactic Distribution of planets: Spitzer Microlens Parallax Measurements of 21 Single-Lens Events

OGLE+Spitzer+ MOA, Wise, MiNDSTEp (Chile+SUO), PLANET (SAAO), RoboNet (LCOGT)

OGLE-2014-BLG0099: $\Delta \chi^2 = 17.33$, 0, 241.54, 202.96 (+,−,+++,−+)

OGLE-2014-BLG0678: $\Delta \chi^2 = 0.47$, 0, 24.57, 3.73 (+,−,++,−+)

Heliocentric velocity (km/s)  Geocentric parallax

$\pi_E$ space degeneracy breaking: $\Delta \chi^2$ and Rich’s argument (1997 ca.)

From the Distribution of (Single) Lens Distances ...

\[ \pi_{rel} = \mu_{geo} t_E \pi_E \]

\[ D / kpc = 1 / \left[ \frac{\pi_{rel}}{\text{mas}} + 1 / 8.3 \right] \]

\[ D_l \sim D \text{ for } D \leq D_s / 2 \]

\[ D_s - D_l \sim 8.3 \text{ kpc} - D \text{ for } D \geq D_s / 2 \]

we find \(~30\%\) of bulge lenses vs \(~60\%\) expected for an unbiased sample: bias from observational protocol

SCN et al 2014, in prep.
.... to the Galactic Distribution of Planets

a test study: 1 planet only! (SCN et al 2014, in prep.)

a key issue: the planetary events are NOT chosen for Spitzer observations because they are known to have planets – they are a fairly-drawn sample from the ensemble of single lens events, regardless of any bias in this sample

a caveat: each point-lens lightcurve pdf must be weighted by the corresponding planet sensitivity (Gould et al 2010), in order to compare the resulting cumulative distribution, namely the cumulative distribution of planet detectability, with the Galactic distribution of planets

Fig. 4 from Gould et al 2010
Conclusions

- First results out of a 100-hr (38 d) Spitzer Microlens Planets and Parallaxes pilot program
  (a caveat) first ever study of a large sample of microlens parallax measurements: ongoing work

- OGLE-2014-BLG-0124L: parallax for a 0.5 $M_{jup}$ (Udalski et al, 2014, sub.)
- OGLE-2014-BLG-0939: first microlensing parallax for an isolated star (Yee et al 2014, sub.)
- Spitzer Microlens Parallax for 21 single lens: Pathway to the Galactic Planet Distribution (SCN et al 2014, in prep)

- Looking forward: increase the number of microlensing planetary events detected in space-based campaign: a larger Spitzer program, Kepler (K2) ...... WFIRST