Interpenetration of
Astrometry and Microlensing
Andy Gould (Ohio State University)
Generation 1

• Liebes 1964, Phys Rev, 133, B835
  • Many practical examples, including planets
  • Mass measurement of Isolated Star
  • Space-Based Parallaxes
  • Proposed First Practical Experiment
Eddington 1920, Space, Time, and Gravitation

Chwolson 1924, Astron. Nachr. 221, 329

Einstein 1936a, Science, 84, 506

“Some time ago R.W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request .... there is no great chance of observing this phenomenon.”

Einstein 1936b (private letter to Science editor)

“Let me also thank you for your cooperation with the little publication, which Mister Mandl squeezed out of me. It is of little value, but it makes the poor guy happy.”
Generation -1: Einstein (1912)

[Renn, Sauer, Stachel 1997, Science 275, 184]

Fig. 1. Notes about gravitational lensing dated to 1912 on two pages of Einstein’s scratch notebook (f2). [Reproduced with permission of the Einstein Archives, Jewish National and University Library, Hebrew University of Jerusalem]
gravitational microlensing by double stars and planetary systems

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1. Geometry of microlensing by a binary, as seen in the sky. The primary of 1 $M_\odot$ is located at the center of the figure, and the secondary of 0.001 $M_\odot$ is located on the right, on the Einstein ring of the primary arc. The radius of the ring is 1.0 mas for a source located at a distance of 8 kpc of the lens at 4 kpc. The two complicated shapes around the primary are.

The effect is strong even if the companion is a planet. A massive search for microlensing of the Galactic bulge stars may lead to the discovery of the first extrasolar planetary systems.
5. OBSERVATIONAL REQUIREMENTS

Two distinct steps are required to observe a planetary system by microlensing. First, one must single out a disk star which happens to be microlensing a bulge star. Second, one must observe this star often enough to catch the deviation in the light curve due to the planet. The first step involves the observation of millions of bulge stars on the order of once per day. The second step involves the observation of a handful of stars many times per day. In the following we give a rough outline of what is required for each of these steps.

While observations from one site would be useful, there are advantages to be gained by observing from several sites. First, two telescopes that were totally committed. Third, in view of the fleeting nature of the events, it would seem prudent to build in some redundancy in case of bad weather at a particular site. Thus, the optimal scheme would employ, say, a dozen telescopes. Each of these would be committed to carry out two observations per night. During the near-December season,
How Microlensing Finds Planets
1995 PLANET Pilot Season

OGLE-2005-BLG-390
“Classical-Followup” Planetary Caustic

Beaulieu et al. 2006, Nature, 439, 437
First “High-Magnification” Planet

Amateurs + Professionals

Grant, Ian, Jennie, Phil
Amateurs + Professionals

"It just shows that you can be a mother, you can work full-time, and you can still go out there and find planets."

Jennie McCormick
(Amateur Astronomer, Auckland, New Zealand)
OGLE-2005-BLG-169:
Second Cold Neptune
Deokkeun An
OGLE-2006-BLG-109: Without Followup Observations
OGLE-2006-BLG-109
Parallax+Finite-Source+Rotation+Blend

Gaudi et al. 2008, Science, 319, 927
Five Lightcurve Features

$1 + 2 + 3 + 5 = \text{Saturn}$  $4 = \text{Jupiter}$
Microlensing vs. Other Methods
Relation of Mass and Distance to Lensing Observables

\[ \alpha = \frac{4GM}{r_E c^2} \]

\[ \psi \]

\[ r_E \]

\[ \alpha \]

\[ \theta_E \]

\[ \tilde{r}_E = \frac{\sqrt{4GM D_{rel}}}{c^2} \]

\[ \theta_E = \sqrt{\frac{4GM}{D_{rel} c^2}} \]

\[ \theta_E \tilde{r}_E = \alpha r_E = \frac{4GM}{c^2} \]

\[ \theta_E = \alpha - \psi = \frac{\tilde{r}_E}{D_l} - \frac{\tilde{r}_E}{D_s} = \frac{\tilde{r}_E}{D_{rel}} \]
To measure angular Einstein radius:

Standard Sky-Plane Rulers

MOA-2007-BLG-400

μFUN CTIO H

μFUN CTIO I

Single Star

Star + Planet

I [instrumental]

(V-I) [instrumental]
To measure parallax:

Standard Observer-Plane Rulers
Another Crackpot Idea:
Terrestrial Microlens Parallaxes

PHOTON STATISTICS LIMITS FOR EARTH-BASED PARALLAX MEASUREMENTS OF MACHO EVENTS

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ABSTRACT

We analyze the limitations imposed by photon-counting statistics on extracting useful information about MACHOs from Earth-based parallax observations of microlensing events. We find that if one or more large (say 2.5 m) telescopes are dedicated to observing a MACHO event for several nights near maximum amplification, then it is possible, in principle, to measure the velocity of the MACHO well issues. We thank Andrew Gould for pointing out an error in the original version of this manuscript. This research was
Terrestrial Parallax:
Simultaneous Observations on Earth

[Diagram showing the concept of terrestrial parallax with a large planet and a smaller Earth diagram with observational points marked on the Earth.]
OGLE-2007-BLG-224
Canaries South Africa Chile
Space-Based Parallaxes & Einstein Radii: SIM

\[ \tilde{r}_e \Delta u = d_{SIM} \]

(b) \[ \tilde{r}_e = \frac{d_{SIM}}{\Delta u} \]

(c)
“Direct Detection” of Lens From Centroid Motion (using known proper motion)
OB-03-235/MB-03-053: 5.5 kpc

Finite Source + Centroid Motion

OGLE-2005-BLG-071: 3.3 kpc
Parallax + Finite Source + Centroid Motion

Dong et al. 2009, 695, 970
OGLE-2006-BLG-109: 1.5 kpc

Parallax + Finite Source + Blend

Gaudi et al. 2008, Science, 319, 927
OGLE-2007-BLG-349: 3 kpc
Parallax + Finite Source + Blend

Dong et al. 2009, in prep
MOA-2007-BLG-192: 1.5 kpc

Parallax + Finite Source

MOA-2008-BLG-310
A Verifiable Bulge Planet?

Janczak et al. 2009, in prep
To Fully Determine Lens Nature: SIM

\[ \tilde{r}_e \Delta u = d_{\text{SIM}} \]

(a)

\[ \tilde{r}_e = \frac{d_{\text{SIM}}}{\Delta u} \]

(b)

(c)
... or, more immediately: **Spitzer**
From a paper written 10 years ago ...

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**MICROLENS PARALLAXES WITH SIRTF**

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\[ t_{0, \oplus} = t_{0, \oplus} + \Delta t_0 , \]

\[ \frac{\Delta t_0}{t_{e, \oplus}} = \Delta u_x \cos \theta - 2(\Omega_{\oplus} t_{e, \oplus})^{-2}\gamma_{\oplus} \sin^2 \theta ; \quad (13) \]

\[ \frac{\sigma_{\Delta u_x}}{\Delta u} = \frac{\sigma_\gamma}{\gamma \sec \phi} = 0.17N^{-1/2} \frac{\sigma_0}{0.01} \frac{\tilde{v}}{275 \text{ km s}^{-1}} \left( \frac{t_e}{40 \text{ days}} \right)^{-3/2} \frac{S(\beta)}{S} . \]

\[ \beta_S = |\beta_{\oplus} \pm \Delta \beta| , \quad \Delta \beta = \Delta u_x \sin \theta + (\Omega_{\oplus} t_{e, \oplus})^{-2}\gamma_{\oplus} \sin 2\theta ; \quad (21) \]

\[ b_{ij} \left( \frac{t_0}{t_e}, \gamma \right) = \frac{64}{u^5(u^2 + 4)^{5/2}(u^2 + 2)\sigma_0^2} \left( \begin{array}{cc} 2\tau^2 & -\tau^4 \\ -\tau^4 & \tau^6/2 \end{array} \right) , \quad (22) \]

\[ \frac{\Delta t_e}{t_{e, \oplus}} = \Delta u_x \Omega_{\oplus} t_{e, \oplus} \sin \theta + (\Omega_{\oplus} t_{e, \oplus})^{-1}\gamma_{\oplus} \sin 2\theta ; \quad (15) \]

\[ \frac{\sigma_{t_0}}{t_e} \sim \left( \frac{25}{12} \right)^{1/2} \beta \sigma_\ast , \quad \sigma_\ast = \left( \frac{5}{3} \right)^{1/4} \left( \frac{\beta^{1/2} \sigma_0}{\tilde{v}} \right) , \quad (16) \]

\[ \gamma_S = \Delta u_x(\Omega_{\oplus} t_{e, \oplus})^2 \cos \theta + \gamma_{\oplus} \cos 2\theta . \]

\[ \left[ \text{at } \tau = \left( \frac{2}{3} \right)^{1/2} \beta \right] , \quad (23) \]
OGLE-2005-SMC-001

CMD

Photometry

Spitzer Obs
Microlens Parallax

~0.45 day

OGLE-2005-SMC-001

• Ground-Based
• Spitzer

Magnitude


Ground

Spitzer
Subo Dong
Halo Macho Dark Matter?

MACHO “yes” / EROS “upper limits”
Space-Based Parallaxes & Einstein Radii: SIM

\[ \tilde{r}_e \Delta u = d_{\text{SIM}} \]

(a)

(b)

(c)
Taking the Measure of the Universe...
We are ready!

Nanometer Control & Picometer Knowledge: Flight Ready Hardware (TRL6)
SIM: Unbiased Galactic Census
By Unraveling Microlensing Events
Conclusions

• Two Paths to Astrometric Microlensing
  – Deflection of Images
  – Photometric deviations

• Many planet distances are measured
  – Contrary to initial expectations

• SIM μas astrometry + space-based parallax will enable an unbiased Galactic census