Astrometric Microlensing with GAIA

Kailash C. Sahu
Space Telescope Science Institute
Photometric Microlensing

\[ R_E^2 = (4GM/C^2) D_L D_{LS}/D_S \]

\[ T_E = R_E/V = [(4GM/C^2) D_L D_{LS}/D_S]^{0.5}/V \]

\[ M_{\text{lens}} = (T_E V C)^2 D_S/(4G D_L D_{LS}) \]

\[ M \text{ depends on } (T_E, D_L, D_S, V) \]

So the mass estimates from timescales are generally statistical in nature.

For nearby stars, velocity and distances are also known.

Photometric microlensing optical depth is small.
Microlensing causes an astrometric shift in the position of the source, which can be observed to large distances.

The astrometric shift:
\[ \delta = \frac{u \Theta_E}{u^2 + 2} \sim \frac{\Theta_E}{u} \] (for large \( u \))
\[ u = \frac{\delta}{\Theta_E}; \quad \delta = \frac{\Theta_E^2}{\delta} \]

Thus \( \delta \) is a direct measure of \( \Theta_E \)
\[ \Theta_E = \frac{R_E}{D_L} = \left[ \frac{(4GM/C^2) D_{LS}}{(D_L D_S)} \right]^{0.5} \sim \left[ \frac{(4GM/C^2)}{D_L} \right]^{0.5} \] (for nearby lenses)

• Astrometric shift, combined with the distance, provides a direct measure of the mass of the lens.
Search for Microlensing Events by Nearby, High-Proper-Motion Stars

- Input catalog: LHS Catalog with improved coordinates from Lepine and Shara (2005) and Bakos, Sahu and Nemeth (2002)
- Nearby and higher PM stars are the most interesting because: (i) Probability of lensing is high (ii) Angular Einstein ring is large, so the deflection is measurable even at large separations
- Projected the positions forward taking proper motion and parallax into account, and searched for encounters within 2 arcsec with stars in the GSC-II catalog (>V~21)
- Two interesting events: Proxima and LHS 451 (see Profts at al. 2011, for other possible events.)
**Proxima Centauri**

- **The nearest star (~4.24 light years)**

- **M star (the most common)**

- Since Proxima is effectively a single star, its mass is determined from its luminosity as 0.12 solar mass, which is model dependent.

- All attempts to detect planets around Proxima have so far been unsuccessful. (No transits observed. RV: No planet with $m \sin i >$ Neptune to 1 AU. Astrometry: No planet with $> Jupiters$ mass with period 1 to 1000 days.)

- Proxima is a “high-proper-motion” star, moving ~3.85 arcsec per year (it moves across the width of the full moon in ~500 years).
Path of Proxima

Reprise of the famous 1919 solar eclipse experiment that confirmed General Relativity: distances are larger, deflections are smaller.

I: Oct, 2014
Impact parameter: 1.6 arcsec
V~20

II: Feb, 2016
Impact parameter: 0.5 arcsec
V~19.5

As Proxima passes in front, it will cause a relativistic deflection of light from the background star, which provides a measure of its mass.

If Proxima has planets, the planets can cause extra deflections, which are measurable.
Deflections due to Proxima and Its Planets

First Source (Oct, 2014)

- Deflection $\delta \theta = (28 \text{ mas})^2/\Delta \theta$
- Impact parameter: 1.6 arcsec
  $V \sim 20$
  maximum deflection ~ 0.5 mas
- Measurable for $>1$ year
Deflections due to Proxima and Its Planets

Second Source (Feb, 2016)

- Max deflection ~ 1.5 mas, V=19.5
- Proxima’s mass can be measured to better than 2%
- A planet causes extra deflection. For a 10 Jupiter-mass planet, the deflection can be up to 2.8 mas.
- Planetary signal lasts few hours to ~3 days.
- If the planet is closer to Proxima, the amplitude of the astrometric signal increases, which can also be used to derive the mass of the planet.
- There is a small probability that photometric microlensing by a planet can be observed. The timescale (~3 days) will provide the mass of the planet.
- GAIA should clearly be able to measure the deflections.
Sensitivity to Planets

Planets (10 Jupiter mass) detectable up to ~4 AU (with HST).

10 Earth-mass planets within the red band

If a planet resides within the green region, it will cause a brightening of the star. This effect would be observable even with small telescopes.
**Nearby Isolated M dwarf LHS 451 (GJ 682)**

- **GJ 682 (LHS 451) is a nearby (D=5.1 pc), isolated, M 3.5 dwarf.**
- **Proper motion 1.175 arcsec/yr.**
- **V=10.95**
- **Since LHS 451 is an isolated star, LHS 451’s mass can only be estimated from M-L relations as ≈0.27M**
- **ΘE**
The 2015 GJ 682 event

- $V$ (source) -13 (only 2 magnitudes fainter than the LHS 451)
- Brightest source among all the expected microlensing events by hpm stars
- Contrast between the lens and the source is minimum.
The 2015 GJ 682 event

This object was observed by HST in ~2000, so the trajectory is precise.

The closest approach is ~0.6 arcsec; expected around August 2015.

Most ideal microlensing event by a nearby star that can be followed up with GAIA

Stein 2051A itself is an unresolved binary with an unresolved companion with orbital period...
Stars with $M > 20 \, M_\odot$ are thought to end their lives as black holes. There should be 100 million BHs in the Galaxy.

A large fraction of them are expected to be isolated, because:
- $\sim 30\%$ start as single stars
- close binaries lead to merging during SN explosion
- very wide binaries produce single BHs due to orbital separation by the “kick velocity”.

Yet, there has never been an unambiguous detection of an isolated black hole.

Microlensing is perhaps the only method capable of detecting solitary BHs.
Mass discrepancy of stellar remnants

• **Masses of NSs and BHs in binary systems:**
  - NS masses \( \sim 1.4\,M_\odot \)
  - BH masses \( \sim 8 \pm 1\,M_\odot \) (Ozel et al. 2010)

• **Theoretical Models:**
  - NS masses \( \sim 1.2–1.6\,M_\odot \)
  - BH masses 3 to 20 \( M_\odot \)

• **Observed BH masses from binaries are a biased and minority sample**
Stellar Mass Black Holes and Microlensing

MOA and OGLE collaborations have detected >7000 microlensing events within the last 10 years.

Some events must be due to isolated neutron stars and stellar-mass black holes.
Microlensing can break the degeneracy

\[ A = \frac{u^2+2}{u(u^2+4)} \]

Amplification is a pure function of \( u \)

The astrometric shift:
\[ \delta = u \frac{\Theta_E}{u^2+2} \]

Thus \( \delta \) is a direct measure of \( \Theta_E \)

\[ \Theta_E = \frac{R_E}{D_L} = \left[ \frac{4GM}{C^2} \right]^{0.5} \frac{D_{LS}}{D_L D_S} \]

- For a 5M\( \odot \) lens, the astrometric shift is \( \sim 1.4 \) mas, easily detectable with HST and GAIA.

- Astrometric shift, combined with the distances provide an unambiguous measurement of the mass of the lens.
• Earth’s motion around the Sun introduces a distortion on the microlensing light curve.

• Such “parallax” measurements provide an estimate of the distance to the lens.
Physical parameters from astrometric microlensing

\[ \theta_E = \frac{R_E}{D_L} = \left[ \frac{(4GM/C^2) D_{LS}}{D_L D_S} \right]^{0.5} \]

- \( \delta, A \Rightarrow \theta_E \)
- Parallax signal \( \Rightarrow D_L \)
- CMD \( \Rightarrow D_S \)

\[ \rightarrow \text{Mass of the Lens} \]

- Unequivocal detection of BHs with measurements of:
  - the mass,
  - the distance and
  - the velocity
  from a single technique.
Observe 5 ongoing, high-magnification, long-duration ($t_E > 100$ days) events with WFC3/HST, and measure:

i. Parallax motion (millimag)
ii. Distance to the source
iii. Astrometric motion (milliarcsec)

Measure the mass of the potential BH, along with its distance and velocity.

-> first unequivocal detections of isolated BHs, with mass measurements.
II. Detecting and Measuring the Masses of Stellar Remnants  
(GO-12586, PI: Sahu)

• Fields/ Targets  
  4 ACS fields, 8 WFC3/UVIS fields, each with ~120,000 stars  
  Total of 1.8 million stars, 50% with astrometric measurements

• Observing Cadence  
  One visit every 2 weeks over 8-months/year, for 3 years  
  Optimized for long-duration events

• Expectations:  
  ~100 microlensing events  
  40% brighter than V=22, with astrometric measurements

  ~several BHs and NSs  
  STARTED IN 2012, Observations ongoing.
Detecting Isolated Black Holes with GAIA

• There are about 3000 microlensing events detected per year by OGLE/MOA.

• About 20 are long-duration events (>80 days), likely to be due to >3 solar mass lenses.

• Most are bright enough for astrometric measurements with GAIA, leading to mass measurements.

• Astrometric microlensing cross section is much higher than photometric microlensing, and astrometric deflection is detectable up to several Einstein ring radii. So GAIA can also detect a number of pure astrometric events (with no photometric counterparts), and lead to their mass measurements.

• Microlensing can potentially lead to GAIA alerts based on astrometry, which can be followed up by facilities such as HST.
Summary

- Passages of nearby, high-proper-motion stars close to background stars provide a unique opportunity to measure the deflection, and determine their masses.

- Proxima Centauri and LHS 451 will pass close to 2 ~19th magnitude stars in 2014 and 2016, with impact parameters 1.6 and 0.5 arcsec. LHS 451 will pass close to a ~13th magnitude star in August 2015. These are two ideal cases for follow-up with GAIA for mass determination, and possible planet detection.

- GAIA can potentially detect and measure the mass of isolated black holes through measurement of the astrometric shifts. Long-duration microlensing events are the best candidates for follow-up.

- GAIA should be able to detect pure astrometric microlensing events caused by isolated black holes, which are photometrically not detected ("potential astrometric alerts"), leading to their mass measurements.