Developing the Exoplanet Mass Measurement Method Using Space Based Observations

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q (planet – host star mass ratio) determined, but planet host star mass and their separation in physical coordinates not determined

space based follow up observations needed

HST Observations & PSF fitting

Elongated target object OGLE-2005-BLG-169 observed in 2012 – 6.5 years after discovery
HST Observations & PSF Fitting

Single Star Fit Residual  Vs  Dual Star Fit Residual
How to know which star is Source?

• In I band both stars have same magnitude – since lens in nearer than the main sequence source so it should be redder than Source - hence Lens is fainter in V and B band (see next slide)

• CTIO V band Source magnitude matches with brighter star of HST V band, hence confirming the source
First Direct Relative (Lens-Source) Proper motion of Planetary Microlens Host Star Measured

\[ \mu_{\text{rel,l}} = 7.39 \pm 0.20 \text{ mas/yr} \]

\[ \mu_{\text{rel,b}} = 1.33 \pm 0.23 \text{ mas/yr} \]

Lens Source brightness similar in I band indicating Lens redder than source hence Lens is also fainter in V and B band.
Proper Motion : Confirmation of Microlensing Planet

- HST: $\mu_{relG} = 7.2 \pm 0.4 \text{ mas/yr}$
- $\mu_{relH}$ changed to $\mu_{relG}$ using probability distribution of $(D_L/D_S)$ from a galactic model$^1$

First Confirmation of Microlens Planet Signal

Proper Motion: Constrains Star - Planet Mass Ratio

- Before:

\[ \mu_{\text{relG}} = \frac{\theta^*}{t^*}. \]  \[ \theta^* \] is unchanged. So \[ t^* \] smaller means \[ \mu_{\text{relG}} \] higher.

Proper Motion: Constrains Star - Planet Mass Ratio

- HST Analysis removes uncertainty in light curve fit parameters

\[ \mu_{\text{relG}} = \frac{\theta^*}{t^*}. \theta^* \text{ is unchanged. So } t^* \text{ higher means } \mu_{\text{relG}} \text{ smaller.} \]
Comparing Results(1): Discovery and Follow Up

Discovery paper light curve\(^1\)

Light curve consistent with HST

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Determination of Host Star and Planet Mass

\[ \theta_E^2 = \frac{4GM_L(D_S - D_L)}{c^2 D_S D_L} \]

Mass – Luminosity

(Henry, McCarthy 1;
Delfosse et al 2;
Henry et al 3;
Kenyon, Hartmann 4)

Constrains \( I_s \) and total target brightness

\[ \frac{M_P}{M_H} = q = 6 \times 10^{-5} \]

Final Results

\[ D_S \sim 8 \text{ kpc} \]

Projected separation \( a_\perp = \theta_E b D_L \) (2D)

Comparing Results(2): Discovery and Follow Up

**Discovery paper**

- $\mu_{\text{relG}} = 8.4 \pm 1.7 \text{ mas/yr}$
- $\alpha \sim 120^\circ$, $q = 8 \times 10^{-5}$
- Host mass: $0.49^{+0.23}_{-0.29} \text{M}_\odot$
- Planet Mass: $\sim 13 \text{M}_\oplus$
- $D_L = 2.7^{+1.6}_{-1.3} \text{kpc}$
- Projected Separation($a_\perp$): 2.7 AU(2d)

**HST**

- $\mu_{\text{relG}} = 7.2 \pm 0.4 \text{ mas/yr}$
- $\alpha \sim 90^\circ$, $q = 6 \times 10^{-5}$
- Host mass: $0.687 \pm .021 \text{M}_\odot$
- Planet Mass: $14.1 \pm 0.9 \text{M}_\oplus$
- $D_L = 4.1 \pm 0.4 \text{kpc}$
- Projected Separation($a_\perp$): 3.5 $\pm$ 0.3 AU(2d)


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Comparing Results (3): HST & Keck

HST vs Keck

Consistent

Look for Virginie Batista’s Talk in afternoon

Future Work and Improvements (1)

• With the magnitudes of Source and Lens known, stars similar in color to Source and Lens (instead of overall target) can be found to extract PSF and fit the target with new PSF model

• Eliminating the effect of nearby bright stars in PSF fitting of target.

Example – MOA -2008-BLG-379

(Follow next 2 slides)
Future Work and Improvements (2)

MOA-2008-BLG-379

From Discovery paper:\[^1\]:
\[ \mu = 7.8 \pm 1.6 \text{ mas/yr} \]
Predicted separation for observations by late 2013:
\[ 37.8 \pm 8.3 \text{ mas} \]
\[ (\sim 1 \text{ HST pixel}) \]

HST Observation of MOA-2008-BLG-379

Future Work and Improvements (1):
Contamination from Nearby star

MOA-2008-BLG-379

Two star PSF fit close up

Probable Solution: Fit 3 star PSF model

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Future Work and Improvements (2)

MOA-2008-BLG-310

• From Discovery paper\(^1\):

\[ q = (3.3 \pm 0.3) \times 10^{-4} \]

Sub Saturn mass planet

\[ \mu_{\text{relG}} = 5.1 \pm 0.3 \text{ mas/yr} \]

• Excess flux in H band (NACO Data)

Future Work and Improvements (2): Reasons for extra flux from Discovery paper

MOA-2008-BLG-310

Possible Reasons for Excess Flux on Source
• Excess flux due to Lens system
  (Unlikely as it requires Lens to be at 300 pc)
• Due to unrelated star
  (Unlikely ~5.1% chance)
• Due to Source Companion
  (Unlikely ~7% chance)
• Due to Lens Companion
  (Unlikely ~4% chance)

We need space based data to determine if excess flux is from Lens

Future Work and Improvements (2):

Two star fit chi^2 contour

MOA-2008-BLG-310

HST WFC3 I band data from Feb, 2012 (3.5 years after peak magnification)

HST WFC3 I band data from Feb, 2014 (5.5 years after peak magnification)
MOA-2008-BLG-310

CHALLENGE!! To determine if excess flux is due to lens and learn about lens system

Future procedure:

1. Analyze V band data and compare
2. Calibrate with ground based data to check if there is extra flux
3. Check PSF in HST WFC3 data analysis
4. Run PSF fit with constraint on Source magnitude
Conclusions & Future Work

- Space based data provides host star and planet mass, their separation, lens distance and First confirmation of Microlens planetary signal.

**Prepares us to deal with future WFIRST microlensing data**

- Demonstrates WFIRST Mass Measurement Method
- Resolved degeneracy in planetary models
- Many such measurements will build statistics for planetary mass function depending on host star mass and distance
- Similar techniques will be used to analyze HST WFC3 IR data which is more like WFIRST