Developing the WFIRST Mass Measurement Method Using HST 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


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HST Observations & PSF fitting

Elongated target object OGLE-2005-BLG-169 observed in 2012 – 6.5 years after discovery

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HST Observations & PSF Fitting

Dual Star Fit Residual

Single Star Fit Residual

Vs
Midpoint and flux centroid are same in I band.

Flux Centroid shifted from midpoint in V band -> Source is brighter than Lens.
HST Observations & PSF Fitting

Midpoint and flux centroid are same in I band

Flux Centroid shifted from midpoint in V band  Source is brighter than Lens

Measuring proper motion

First Direct Proper motion of Planetary Microlens Host Star Measured
HST Observations & PSF Fitting

Centroid in I band

Centroid in V band

Centroid shift implies Source star has higher flux ratio
Fit between dual star and single star model
Green predicts $\mu_{\text{rel}}$ from light curve

$\mu_{\text{rel}} = 7.2 \pm 0.4$ mas/yr

First Confirmation of Microlens Planet
Proper Motion: Constrains Star - Planet Mass Ratio

• Before:

Proper Motion: Constrains Star - Planet Mass Ratio

- Now:

Comparing results(1): Discovery and Follow Up

Discovery paper light curve

Light curve consistent with HST

Determinaton of Host Star and Planet Mass

\[ \theta_2 E = 4 \frac{G M_L (D_S - D_L)}{c^2 D_L D_S} \]

Mass – Luminosity
(Henry, McCarthy\(^1\); Delfosse et al\(^2\); Henry et al\(^3\); Kenyon, Hartmann\(^4\))

Constrains \( I_s \) and total target brightness

Final Results

\[ M_L = M_P + M_H \]
\[ M_P / M_H = q = 6.0 \times 10^{-5} \]

Projected separation \( a_\perp \)

\[ D_S \sim 8 \, \text{kpc} \]
\[ a_\perp = \theta_E b D_L \]
(2D)


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Determination of Host Star and Planet Mass

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

Mass – Luminosity

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

Constrains \( I_s \) and total target brightness

\[ M_L = M_P + M_H \]
\[ \frac{M_P}{M_H} = q = 6.0 \times 10^{-5} \]

Final Results

\( M_H, M_P \)

Projected separation \( a_\perp \)

\[ D_S \sim 8 \text{ kpc} \]
\[ a_\perp = \theta_E b D_L \]

Comparing Results (2): Discovery and Follow Up

<table>
<thead>
<tr>
<th>Discovery paper</th>
<th>HST</th>
</tr>
</thead>
<tbody>
<tr>
<td>µ_{rel} = 8.4 ± 1.7 mas/yr</td>
<td>µ_{rel} = 7.2 ± 0.4 mas/yr</td>
</tr>
<tr>
<td>α ~ 120°, q = 8.e-05</td>
<td>α ~ 90°, q = 6.e-05</td>
</tr>
<tr>
<td>Host mass: 0.49^{+0.23}_{-0.29} M\odot</td>
<td>Host mass: 0.687 ± .021 M\odot</td>
</tr>
<tr>
<td>Planet Mass: ~13 M\oplus</td>
<td>Planet Mass: 14.1 ± 0.9 M\oplus</td>
</tr>
<tr>
<td>D_{L} = 2.7^{+1.6}_{-1.3} kpc</td>
<td>D_{L} = 4.1 ± 0.4 kpc</td>
</tr>
<tr>
<td>Projected Separation(a_{⊥}): 2.7 AU(2d)</td>
<td>Projected Separation(a_{⊥}): 3.5 ± 0.3 AU(2d)</td>
</tr>
</tbody>
</table>

Comparing Results (3): HST & Keck

<table>
<thead>
<tr>
<th>HST</th>
<th>Keck</th>
<th>8.3 years after discovery$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{\text{rel}_l}$ = 7.39 ± 0.20 mas/yr</td>
<td>$\mu_{\text{rel}_l}$ = 7.28 ± 0.12 mas/yr</td>
<td></td>
</tr>
<tr>
<td>$\mu_{\text{rel}_b}$ = 1.33 ± 0.23 mas/yr</td>
<td>$\mu_{\text{rel}_b}$ = 1.54 ± 0.12 mas/yr</td>
<td></td>
</tr>
</tbody>
</table>

Both supports $\alpha \sim 90^\circ$ and $q = 6.0 \times 10^{-5}$ model

- Host mass: 0.687 ± 0.021 $M_\odot$
- Planet Mass: 14.1 ± 0.9 $M_\oplus$
- $D_L = 4.1 \pm 0.4$ kpc
- Projected Separation($a_\perp$): 3.5 ± 0.3 AU

- Host mass: 0.667 ± 0.049$M_\odot$
- Planet Mass: 13 ± 1.5 $M_\oplus$
- $D_L = 3.9 \pm 0.4$ kpc
- Projected Separation($a_\perp$): 3.4 ± 0.3 AU

1. Batista et al. - in preparation
Conclusions & Future Work

- Space based data provides host star and planet mass, their separation, lens distance.

**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
THANK YOU