Jean-Philippe Beaulieu & Daniel Kubas

High angular resolution imaging of microlensing

Institut d’Astrophysique de Paris
Cook book references:

Kubas et al. 2011, A&A in press (MOA 192 final analysis)

Sumi et al., 2010, ApJ 710, 1641 (OGLE 368, Neptune planet)

Tools:
- Dophot, Daophot, starfinder (PSF fitting code)
  (http://www.eso.org/sci/publications/messenger/archive/no.100-jun00/messenger-no100-23-27.pdf)
- Jitter/Eclipse infrared data reduction package :
  (http://www.eso.org/sci/software/eclipse/)
- skycat/gaia (astrometry http://starlink.jach.hawaii.edu/starlink)
- Topcat (catalogue manipulation http://www.star.bris.ac.uk/~mbt/topcat/)
- 2MASS catalogue (calibration http://www.ipac.caltech.edu/2mass/)
Menu

1/ Why we need AO or HST images?

2/ Example of MOA 192 (in details)

3/ Some remarks about other events (MOA 310, OGLE 266, etc)
"Seeing" the lens

Observed light curve flux:

\[ F(t) = F_A(t) + F_B \]

Amplification due to lens

unlensed source flux

blend flux

\[ F_B = F_{\text{lens}} + F_{\text{Background}} \]

Idea: separate event from unrelated background using space-based or AO high resolution imaging (ideally at 2 epochs)

-> using the lens model, the lens (planet host star) flux can be measured.

-> Improves accuracy of physical lens parameters by an order of magnitude!
Detection light from the lens & measuring direction of proper motion

1/ If relative lens proper motion $\mu_{\text{rel}}$ is known, while the angular Einstein ring is

$$\theta_E = \mu_{\text{rel}} t_E$$

It is a mass distance relation for the lens!

$$M_L = \frac{c^2}{4G} \theta_E^2 \frac{D_S D_L}{D_S - D_L}$$

2/ We adopt a mass-luminosity relation

3/ We need to constraint light from the lens (AO obs + model)

Measure $F(t_1)$ and $F(t_2)$ with $A(t_1) > 1$ and $A(t_2) = 1$
Simulations by Anderson for OGLE 169

HST, ACS, F814W

Residual due to lens moving out

$M_*=0.08 \text{ Mo}$

$M_*=0.35 \text{ Mo}$

$M_*=0.63 \text{ Mo}$

Detecting light from the lens, direction and amplitude of proper motion
First detections by HST [Alcock et al 2001, Kozlowski et al 2007]

Macho-1995-blg-37 (Kozlowski et al 2007)
First detections by HST [Alcock et al 2001, Kozlowski et al 2007]

Ok, it works, let’s do it on planetary microlensing events!
Parameter space exploration of MOA 192

Bennett et al., 2008 ApJ
The different caustic structures of MOA 192

Bennett et al., 2008 ApJ
Getting direction of proper motion would be cool!

Bennett et al., 2008 ApJ

Fig. 8.— The regions of microlensing parallax parameter space that are consistent with the MOA-2007-BLG-192 light curve are indicated by the distribution of $\Delta \chi^2$ from the best fit model. The $\pi_E$ and $\phi_E$ values that are not shown and those that are indicated by white squares all give $\Delta \chi^2 > 12$ larger than the minimum value.
Fig. 9.— The mass-distance relations are plotted in black for the two local minima in the microlensing parallax parameter $\chi^2$ surfaces shown in Fig. 8. The red curves show the probability distributions from a Bayesian analysis that compares the $\tilde{v}$ for each model to a standard Galactic model. The vertical red lines indicate the median distance and lens primary mass and the light red shaded regions indicate the 1-$\sigma$ and 2-$\sigma$ limits on the lens distance and mass. The median and 1-$\sigma$ limits for the lens star mass are $M = 0.036^{+0.057}_{-0.020} M_\odot$ and $M = 0.039^{+0.051}_{-0.020} M_\odot$ for the best and 2nd best fits, respectively. The 2-$\sigma$ ranges are $0.005 M_\odot \leq M \leq 0.36 M_\odot$ and $0.007 \leq M \leq 0.31 M_\odot$. 

\[ \pi_\epsilon = 1.5 \]
\[ \phi_\epsilon = 212^\circ \]

\[ \text{best fit} \]

\[ M_{\text{lens}} \]

\[ D_{\text{lens}} \text{ (kpc)} \]

\[ \text{Likelihood} \]

\[ 0 \]
\[ 0.01 \]
\[ 0.1 \]
\[ 0.2 \]
\[ 0.4 \]
\[ 0.6 \]
\[ 0.8 \]
\[ 1 \]

\[ 0 \]
\[ 2 \]
\[ 4 \]
\[ 6 \]

\[ \pi_\epsilon = 1.3 \]
\[ \phi_\epsilon = 333^\circ \]

\[ \text{2nd best fit} \]
<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>2-σ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>$0.060^{+0.028}<em>{-0.021} M</em>\odot$</td>
<td>$0.024$–$0.128 M_\odot$</td>
</tr>
<tr>
<td>$m$</td>
<td>$3.3^{+4.9}<em>{-1.6} M</em>\oplus$</td>
<td>$1.0$–$17.8 M_\oplus$</td>
</tr>
<tr>
<td>$a_\perp$</td>
<td>$0.62^{+0.22}_{-0.16}$ AU</td>
<td>$0.33$–$1.14$ AU</td>
</tr>
<tr>
<td>$D_L$</td>
<td>$1.0 \pm 0.4$ kpc</td>
<td>$0.5$–$2.0$ kpc</td>
</tr>
<tr>
<td>$I_S$</td>
<td>$21.44 \pm 0.08$</td>
<td>$21.31$–$21.61$</td>
</tr>
<tr>
<td>$q$</td>
<td>$1.8^{+1.9}_{-0.8} \times 10^{-4}$</td>
<td>$0.5$–$7.1 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
MOA 2007-BLG-192: a bit of frustration

Incomplete light curve coverage -> degeneracy in lens models
Lack of strong constraint on source radius -> poorly known RE

Therefore, large uncertainty in physical parameters.
Can VLT/NACO see the lens?
AO photometry is “tricky”

- PSF is not analytical and space+time variant + sky background varies too in NIR

NACO, 28 x 28”, H band
MOA 2007-BLG-192 :

- 2 VLT NACO epoch in JHK : 27”x27” with pixels of 0.02715”
  - Jitter mode (10”) + Natural Guide star

- IRSF (1.4m in Sout Africa) in JHK 8’ x8’ with pixels of 0.45”

<table>
<thead>
<tr>
<th>Band</th>
<th>n × Exp [s]</th>
<th>MJD</th>
<th>Airmass</th>
<th>FWHM [”]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Epoch 1</td>
<td>A=1.23</td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>6 × 60</td>
<td>54350.00781250</td>
<td>1.005</td>
<td>0.14</td>
</tr>
<tr>
<td>H</td>
<td>20 × 25</td>
<td>54350.02734375</td>
<td>1.023</td>
<td>0.19</td>
</tr>
<tr>
<td>Ks</td>
<td>10 × 25</td>
<td>54349.98828125</td>
<td>1.002</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Epoch 2</td>
<td>A=1.0, baseline</td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>23 × 60</td>
<td>55036.08593750</td>
<td>1.015</td>
<td>0.34</td>
</tr>
<tr>
<td>H</td>
<td>22 × 30</td>
<td>55036.06640625</td>
<td>1.034</td>
<td>0.29</td>
</tr>
<tr>
<td>Ks</td>
<td>24 × 30</td>
<td>55015.10156250</td>
<td>1.088</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Using Starfinder [Diolaiti et al. 2002]

Creating numerical psf-template to fit from stars in the fov

Remaining problem photometric calibration!
std zps too “expensive” and different in sky/ background/ time
STARFINDER processing
JHK IRSF fits image

JHK NACO fits image

2MASS Catalogue

Topcat + Gaia/skycat

JHK IRSF Calibrated catalogues Astrometry+photometry

PSF fitting

Eclipse+starfinder + fitting

Topcat + Gaia/skycat

JHK NACO Calibrated catalogues Astrometry+photometry
Some cooking basics

- STARFINDER can handle spatially variant PSFs to correct for the anisoplanatism. (Daophot, Dophot don’t)

- For calibration: check crowding 1 2MASS star could be several IRSF stars

- Calibration stars could be variable (check with MOA and OGLE)

- Do, re-do, get your mates to double check, do again the calibration.
MOA 2007-BLG-192:
Hunting for the source and the lens in J, H, K.
$A_H = 0.46$

$A_K = 0.29$

$dm = 14.38$

$\log (\text{age}) = 9.00 \ 9.88 \ 10.15$

A star, $0.084^{+0.015}_{-0.012}$ $M_\odot$ at $660^{+100}_{-70}$ pc

A planet, $3.2^{+1.8}_{-1.8}$ $M_\oplus$ at $0.82^{+0.51}_{-0.22}$ AU

Previous results

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>2-$\sigma$ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>$0.060^{+0.028}<em>{-0.021}$ $M</em>\odot$</td>
<td>0.024–0.128$M_\odot$</td>
</tr>
<tr>
<td>$m$</td>
<td>$3.3^{+4.9}<em>{-1.6}$ $M</em>\oplus$</td>
<td>1.0–17.8$M_\oplus$</td>
</tr>
<tr>
<td>$a_\perp$</td>
<td>$0.62^{+0.22}_{-0.16}$ AU</td>
<td>0.33–1.14 AU</td>
</tr>
<tr>
<td>$D_L$</td>
<td>$1.0 \pm 0.4$ kpc</td>
<td>0.5–2.0 kpc</td>
</tr>
<tr>
<td>$I_S$</td>
<td>$21.44 \pm 0.08$</td>
<td>21.31–21.61</td>
</tr>
<tr>
<td>$q$</td>
<td>$1.8^{+1.9}_{-0.8} \times 10^{-4}$</td>
<td>0.5–7.1 $\times 10^{-4}$</td>
</tr>
</tbody>
</table>
But it is not enough! We need to detect direction of proper motion...
Stay tune, HST program to do it
(Bennett et al., cycle 20)
A 74 ±17 M$_\odot$ planet at 1.25 ±0.19 AU of a 0.67±0.14 M$_\odot$ star in the Bulge

Amateur with 40 cm used to Trigger the VLT NACO

Janczak et al., 2009
Light detected from the lens
A $20^{+7}_{-8} \, M_{\oplus}$ planet at $3.3^{+1.4}_{-0.8} \, AU$

of a $0.64^{+0.24}_{-0.26} \, M_{\odot}$ star in the Bulge

Sumi et al., 2010
An upper limit on light from the lens magK > 18.1 at 3 sigma

Sumi et al., 2010
NACO images of MOA-2007-BLG-197

MOA-2007-BLG-197
Danish 1p5 @ MHJD=4343.61, I–band

NACO VLT @ MHJD=4333.04, circle = 1″, J–band
Conclusion:

- Important to get HR image to detect/constraint light from lens.
- Read Anderson, Bennett, Gaudi, 2007 and Kubas et al. 2011

- Get cross checks for calibrations
- Several steps (2MASS, IRSF, VLT/KECK/SUBARU/GEMINI et al.)
- Absolute photometry on AO image is not easy, but few percent is doable.
- Do double blind analysis to get secure numbers
- Detecting light from lens with AO (2 epochs).
- Detecting centroid shift is more for HST.

We need telescope time VLT, KECK, GEMINI, SUBARU, HST
We need you to swamp the time allocation committees!