Planet frequency beyond the snow line from MOA-II microlensing survey

Daisuke Suzuki
Osaka University

June 03, 2014 @Boston Westin Copley Place
Exoplanets We Have Known

- Radial Velocity
  - A-M type stars
- Transit
  - FGK type stars
- Microlensing
  - KM type stars
- Direct Imaging
  - A-M type stars
- Kepler planets
  - G type stars

http://exoplanet.eu/
We have known that the snow line is at $a_{\text{snow}} = 2.7 \left( M/M_{\text{Sun}} \right) \text{AU}$.

The diagram shows the distribution of exoplanets with respect to their masses and semimajor axes. The snow line is indicated by a vertical dashed line.

- Radial Velocity
  - A-M type stars
- Transit
  - FGK type stars
- Microlensing
  - KM type stars
- Direct Imaging
  - A-M type stars
- Kepler planets
  - G type stars

For more information, visit [http://exoplanet.eu/](http://exoplanet.eu/)
Gravitational Microlensing

Event timescale: \( t_E \)

\[ t_E \propto \sqrt{M} \]

Solar mass \( \sim \) 30 days

Jupiter mass \( \sim \) a few days

Earth mass \( \sim \) a few hours
Cold Planet Mass Function from Microlensing

- Sumi et al. 2010
  - 10 planets, \( f \propto q^{-0.68\pm0.2} \)

- Gould et al. 2010
  - 6 planets in 13 high-mag events
  - \( 0.36\pm0.15 \) @ \( q \sim 5\times10^{-4} \)

- Cassan et al. 2012
  - 2002 – 2007 OGLE, PLANET data
  - 2 additional planets together with the above.

This work: derive planet frequency beyond the snow line from MOA-II observations in 2007-2012 including 21 planets.
MOA (since 1995)
(Microlensing Observations in Astrophysics)
( New Zealand/Mt. John Observatory, Latitude: 44°S, Alt: 1029m )

Mirror: 1.8m
CCD : 80M pix.
FOV : 2.2 deg.
Filter : MOA-Red
(R + I)
Galactic Bulge Fields (~42 deg$^2$)

- # of μlens alerts
  - 2007: 488
  - 2008: 477
  - 2009: 563
  - 2010: 607
  - 2011: 485
  - 2012: 680
  - 2013: 668

3300 events in 6 yrs

http://www.massey.ac.nz/mao
Event Selection

We reject ...

1. Non-microlensing events (CVs, moving objects, ...)
2. Non-planetary anomalies (stellar binary: $q > 0.03$)
3. Events with insufficient data points

Remaining events are

1471 single lens and 21 planetary candidate events

To derive planet frequency, we should consider detection efficiencies for planetary anomalies
Detection Efficiency, $\varepsilon(\log s, \log q)$

$s$: separation
$q$: mass ratio
$\vartheta$: angle from the axis
$\rho_*$: source star size
Data quality...

Detection:
\[ \Delta \chi^2 = \chi^2_{\text{Single}} - \chi^2_{\text{Binary}} > 100 \]

$\varepsilon(\log s, \log q)$:
Fraction of detections within $0 < \vartheta < 2\pi$

Rhie et al. 2000
\( S(\log s, \log q) \implies S(\log a, \log m_p) \)

Sum of the detection efficiency in each event

**Bayesian Estimate**

- Use \( t_E \) in each event
- With mass function (Sumi et al. 2011, Table3 model #1)
- With Galactic model (Han & Gould 2003)

\[ M_{\text{Lens}} = 0.32^{+0.41}_{-0.23} M_{\text{Sun}} \]
Likelihood Analysis

Planet mass function:

\[ F \equiv \frac{dN}{d\log a \ d\log m_p} = F_0 \left( \frac{m_p}{m_0} \right)^\alpha \]

Likelihood:

\[ \mathcal{L}(F_0, \alpha) = \prod_j P(k_j | E_j) \]

Survey Sensitivity

21 Planet Detections

\[ E = \int \int S(\log a, \log m_p) F(\log a, \log m_p) d\log a \ d\log m_p \]

Expected number of the detection with any given \( F \)

\[ P(k | E) = \frac{E^k \exp(-E)}{k!} \]

Poisson distribution, \( k \) : # of planet detections

\[ F_0 = 10^{-0.67 \pm 0.10} \]

\[ \alpha = -0.78 \pm 0.12 \]

\[ m_0 = M_{\text{Saturn}} \approx 95.2 M_\oplus \]
Planet Mass Function (Microlensing VS RV)

Consistent with previous microlensing results

\[ N: \text{Planet abundance} \]
\[ N = \iint F_0 \left( \frac{m_P}{m_0} \right)^\alpha \, d\log a \, d\log m_P \]

Within 0.5 – 10 AU

- \(15^{+4}_{-3}\) %
  (Giants: 0.3 \(M_{\text{Jup}}\) - 10 \(M_{\text{Jup}}\))
- \(52^{+18}_{-15}\) %
  (Neptunes: 10 \(M_{\text{Earth}}\) - 30 \(M_{\text{Earth}}\))
- \(1.6^{+0.52}_{-0.42}\) planets per star
  (5 \(M_{\text{Earth}}\) - 10 \(M_{\text{Jup}}\))
Discussion

From MOA survey in 2007-2012,

- Consistent with RV for long period giants around M dwarfs: **Bonfils+ 2013, Montet+ 2013**
- More cold giants than close-in Jupiters around M dwarfs: **Johnson+ 2010**

Future: to reduce the uncertainties in planet and host star masses
- Statistics of the events with mass measurements
  - MOA, OGLE, WISE, KMTNet (2nd gen. survey from ground)
  - WFIRST
Summary

From MOA survey in 2007-2012,

- \( F = F_0 (m_P/m_0)^\alpha \), \( F_0 = 10^{-0.67 \pm 0.10} \), \( \alpha = -0.78 \pm 0.12 \)
- Consistent with previous \( \mu \)lensing results
- Consistent with RV for long period giants around M dwarfs:
  - \textbf{Bonfils+ 2013, Montet+ 2013}

- More cold giants than close-in Jupiters around M dwarfs:
  - \textbf{Johnson+ 2010}

- Could be difficult to explain by core accretion theory
- Future: Statistics of the events with mass measurements