Multiplicity of Planets among Small Stars

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Sun
1 \( R_\odot \)
1 \( M_\odot \)
5800 K
8 planets, \( \sim 2 \) in HZ, aligned within 7°

Kepler-186
0.47 \( R_\odot \)
0.48 \( M_\odot \)
3800 K
\( \geq 5 \) planets, \( \geq 1 \) in HZ, aligned within 8°
Result from *Kepler*:
2 planets found

Visualization by Yale grad student John Moriarty
Result from *Kepler*:
2 planets found

Visualization by Yale grad student John Moriarty
Result from *Kepler*:
1 planet found
Multiplicity Among the M Dwarfs

From the NExSci KOI Database, queried on 4 July 2013

- Fang & Margot (2012) for solar-type stars: at least 1-2 planets/star with orbital periods <200 days, vast majority with <3° mutual inclination

- Fabrycky et al. (2012) for all the Kepler multis: 1-2° mutual inclination

- Swift et al. (2013) extrapolating from Kepler-32: 5 planets/star, 1-1.5° mutual inclination
Multiplicity Among the M Dwarfs
Multiplicty Among the M Dwarfs

We have in hand:

\[ \{M\} \]

How likely is \( M \), given a universe with

- \( N \) planets per star
- that have a scatter \( \sigma \) in their mutual inclinations

\[ P(\{M\}|N, \sigma) \propto \prod_i M_i \]

Poisson likelihoods of getting \( M_i \) multis, compared to what we expect, given \( \mu(N, \sigma) \)

Evaluated empirically
One Mode of Planet Formation: Fit to All Data

- Underpredicts number of singles
- Overpredicts number of doubles

Ballard & Johnson (2014)
One Mode of Planet Formation: Fit to Multis

- Really underpredicts number of singles
- All multis replicated

The Solar System

Ballard & Johnson (2014)
Invoking Two Modes of Planet Formation

\[ P(\{M\}|N, \sigma) \propto \prod_i \frac{\mu(N, \sigma)^{M_i} e^{\mu(N, \sigma)}}{M_i!} \]

\[ \mu'(N, \sigma) = (1 - f)\mu(N, \sigma) + f \cdot \delta(i = 1) \]

The original population \( \mu(N, \sigma) \) occurs sometimes

Supplemented by a population of singly transiting planets the rest of the time

We now evaluate posteriors of \( N, \sigma, \) and \( f \)
One Mode of Planet Formation: Fit to Multis

Invoking *ad hoc* a population of singly transiting planets...

Ballard & Johnson (2014)
Two Modes of Planet Formation: Fit to All Data

Ballard & Johnson (2014)

Range consistent with transit duration ratios, per Fabrycky et al. (2014) $f = 0.55 \pm 0.15$, $\sigma = 2.0^{-2.0}_{+4.0}$ degrees

Relaxing assumptions about 2nd population

Ballard & Johnson (2014)
Two Modes of Planet Formation: Fit to All Data

What produces the dichotomy?

Could self-excitation be responsible?
   No: Johansen et al. (2012), Becker & Adams (2015, in prep)

Or does the dichotomy originate during formation?
   Yes: Johansen et al. (2012)
We are exploring dynamical evolution of km-size particles, distributed across a grid of surface density power laws and total mass.

Produce predictions for multiplicity of transits, duration distribution, and period distribution.

More clues from observables!

- Stellar age (stellar rotation period, stellar rotation amplitude, galactic height)
- Metallicity
- Planet size (Johansen et al. 2012)
- TTV fraction (Xie et al. 2014)
Even modest eccentricities can sterilize the surface of M dwarf planets!
Conclusions

Kepler multiples inform our understanding of the true number of planets per star, and their inclinations.

Stars hosting 2 or more planets can be explained with a single model similar to the Solar System, but too many singles to be consistent with this model (robust to selection effects). There are at least five planets per star in these systems.

The data better support two scenarios (where each occurs ~50% of the time) by 21:1 odds. Whether dichotomy originates during formation or subsequently, or some combination, remains to be solved!
Does anything distinguish hosts of singles, versus hosts of multiples?
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**Height above galactic midplane**

- **Modestly distinct**
  - Only K > 13.0
  - K-S statistic = 0.25
  - Significance = 0.20

The diagram shows the distribution of height above the galactic midplane with histograms and cumulative distribution functions. The significance of the distinction is indicated by the K-S statistic and the level of significance.
Does anything distinguish hosts of singles, versus hosts of multiples?

Tantalizing evidence (2σ) that the multiplistic, coplanar systems reside:

- Around more rapidly rotating stars
- Closer to the midplane
- Around metal-poorer stars
Outline

• Why M dwarfs? And why recently?

• What is a “typical” exoplanetary architecture in the universe?

• Multiplicity and habitability: what’s next?
  • The ultimate goal, and the roadmap to get there
Close to home…

Apparent size of planet

Titan

Optically thin

Optically thick

Robinson et al. 2014
...and further afield

Model C1: Medium Ocean Planet

JWST, NIRSpec, 10 transits, 28 hours
M3V, J=8, P=29 day, τ=1.4 hours
“Major Spectroscopic Features and Signal-to-Noise of a Transiting Earth for a Total Co-added Observation Time of 200 hr, for a 6.5 m Space-Based Telescope for the Sun and M stars”

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Kaltenegger & Traub (2009)

...assuming every transit is observed, 200 hours of transit data for a planet in the habitable zone of an M3V star (period of 25 days) will require a 4.9 year baseline
MIT-led Mission: NASA, Orbital Sciences, Harvard-SAO

Discover Transiting Earths and SuperEarths around Bright, Nearby Stars

- Rocky planets
- Water worlds
- Habitable zone planets

Discover 1000+ Exoplanets

All Sky Survey of Bright Stars

- ~40000 deg² (~400 x Kepler)
- F, G, K dwarf stars: 4.5 to 12 magnitude
- M stars known within 50 pc (= 150 l-yr)
- 500,000 stars in two years
Discovered by:

- Ground-based Surveys (MEarth)
- CoRoT
- Kepler Earths & Super-Earths
- Kepler Neptunes and Jupiters
Rocky!

Discovered by:

Ground-based Surveys (MEarth)

CoRoT

Kepler Earths & Super-Earths

Kepler Neptunes and Jupiters
Favorable planet/star radius ratio!

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Discovered by:

Ground-based Surveys (MEarth)

CoRoT

Kepler Earths & Super-Earths

Kepler Neptunes and Jupiters
~a handful of *Kepler* planets

Dozens of *TESS* planets

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Figure from D. Charbonneau
Conclusions

Kepler multiples inform our understanding of the true number of planets per star, and their inclinations.

Stars hosting 2 or more planets can be explained with a single model similar to the Solar System, but too many singles to be consistent with this model (robust to selection effects).

The data better support two scenarios (where each occurs ~50% of the time) by 21:1 odds. Metallicity, rotation period, and galactic height modestly predictive.

The big picture: setting ourselves up for the highest exoplanet science return for JWST.
Selection Bias Sanity Check

Black = singles, Red = multiples

Overall noisiness of light curve

K-S statistic = 0.15
Significance = 0.59
Pair Discussion

• How is the transit affected by:
  – Planet size?
  – Planet mass?
  – Star mass?
  – Semi-major axis?

• Would you expect to see more or less planets in transit for a system that had an inclination slightly less than 90 degrees?
“The Well-Tempered Exoplanets”

![Graph showing the relationship between mass and radius of exoplanets, with discovery dates and planet names indicated.](Image)
Synthetic transits around sun:

A = close-in Earth
B = variable star
C = Jupiter
D = “Neptune” (5 $R_E$)
E = “SuperEarth” (10 $R_E$)
F = binary star

All images: $R_{\text{star}} = 1.0 \, R_{\text{sun}}$
What Can We Learn From Transits?

Primary Eclipse
Measure size of planet
See star’s radiation transmitted through the planet atmosphere.
Used high-resolution visible spectrometer or lower-res IR

Secondary Eclipse
See planet thermal radiation disappear and reappear
Both “filter” spectroscopy and true spectroscopy used.

Learn about atmospheric circulation from thermal phase curves
In some cases, the planet’s atmosphere is sufficiently “puffy” that light from the star can pass through it during the transit. Molecules in the planet’s atmosphere can be detected this way.
Transmission Spectroscopy

- Differential observations taken at different filter bands in and out of transit.
Secondary Eclipse

• Builds on the transit discovery to characterize the planet
  – Technically a “direct detection” method.

• Uses a telescope to watch the planet pass BEHIND its parent star.

• This "secondary eclipse" can be measured to determine exactly how much light is coming from just the planet.
  – Works best in the IR where $L_s/L_p \sim 100$ vs in the visible, where $L_s/L_p > 10000$
  – Secondary eclipses at different infrared wavelengths reveal planetary temperature, composition and the shape of the planetary orbit.
Transits at Different Wavelengths

How big is this planet?
What differences can you see between the lightcurves?

Spitzer: Richardson et al., 2006.
Limb Darkening

• Limb darkening: the diminishing of intensity in a star image from the center to the edge or “limb”.

• Longer pathlengths at the limb reach $\tau=1$ at a higher, cooler atmospheric levels.

• At blue wavelengths small changes in temperature result in large drops in brightness.

• At red and infrared wavelengths changes in temperature result in very small changes in brightness.

• Stars look a different size at different wavelengths

Knutson et al. 2006