Properties of exoplanets and systems with Kepler

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Astronomy Colloquium
March 10, 2015
Collaborators

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Graduate Students:
Jason Hwang, Sam Hadden, Robert Morehead

Undergraduate Students:
Lauren Barmore, Emily Ellinger, David Lee, Remy Millman, David Rice

Funding through NASA’s Kepler Participating Scientist Program and NASA’s Origins Program
Theory of Planet Formation

Nebular theory of planet formation is largely unchanged after more than 200 years – planets form from a gaseous disk.
## Solar System Data

**Revised: Dec 12, 2013**

### Neptune

<table>
<thead>
<tr>
<th>Physical Data (update 2009–May–26):</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (10^{24} \text{ kg})</td>
<td>102.41</td>
</tr>
<tr>
<td>Equatorial radius (1 bar)</td>
<td>24766(+–15 \text{ km})</td>
</tr>
<tr>
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</tr>
<tr>
<td>Density (\text{g/cm}^3)</td>
<td>1.638</td>
</tr>
<tr>
<td>Polar radius (km)</td>
<td>24342(+–30 \text{ km})</td>
</tr>
<tr>
<td>Flattening</td>
<td>0.0171</td>
</tr>
<tr>
<td>Rotation period (16.11(+–0.01 \text{ hr})</td>
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</tr>
<tr>
<td>Rot. rate (10^{–4} \text{ rad/s})</td>
<td>1.083</td>
</tr>
<tr>
<td>Hydrostatic flat., (\text{fh})</td>
<td>0.01804</td>
</tr>
<tr>
<td>Inferred rot. period (16.7(+–1.4 \text{ hr})</td>
<td></td>
</tr>
<tr>
<td>(\text{I/\text{MRo}^2}) (upper bound)</td>
<td>0.239</td>
</tr>
<tr>
<td>(\text{Y factor (He/H ratio)})</td>
<td>0.235(+–0.040 \text{ km}^3/\text{s}^2)</td>
</tr>
<tr>
<td>(\text{GM (km}^3/\text{s}^2)</td>
<td>6,835,107</td>
</tr>
<tr>
<td>Equatorial grav., (\text{ge (m/s}^2)</td>
<td>11.15</td>
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<tr>
<td>Visual magnitude (V(1,0))</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>164.79132 yr</td>
</tr>
<tr>
<td>Mean daily motion</td>
<td>0.006020076(\text{dg/d})</td>
</tr>
<tr>
<td>Mean orbit velocity</td>
<td>5.4778 km/s</td>
</tr>
<tr>
<td>Atmos. temp. (1 bar)</td>
<td>72(+–2 \text{ K})</td>
</tr>
<tr>
<td>Planetary Solar Const</td>
<td>1.47 \text{ W/m}^2</td>
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<tr>
<td>Heat flow/mass (\times 10^7)</td>
<td>2 \text{ erg/gm}^s</td>
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<tr>
<td>Dipole tilt/offset</td>
<td>47deg/0.55Rp</td>
</tr>
<tr>
<td>Escape velocity (\text{km/s})</td>
<td>23.5</td>
</tr>
<tr>
<td>Mag. dip. mom. (gauss–(Rp^3)</td>
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<tr>
<td>Aroche(ice)/(Rp)</td>
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*Solar System Ephemeris, JPL*
### Solar System Data

**Neptune**

**PHYSICAL DATA (update 2009–May–26):**

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**Density (g/cm^3)**: 1.638  
**Polar radius (km)**: 24342±30  
**Flattening**: 0.0171  

**Rot. rate(10^-4 rad/s)**: 1.083

GM 1-sigma (km^3/s^2): ±15  
Pol. grav, gp (m/s^2): 11.41±0.03  

**Obliquity to orbit**: 29.58°  
**Sidereal orbit period**: 60190.029 d  
**Mean orbit velocity**: 5.4770 km/s  

*Solar System Ephemeris, JPL*
Given our knowledge of the solar system, what role can exoplanets play?
1995

Who ordered that?
1800 Confirmed planets
(about ½ from Kepler)

4200 Planet Candidates
(from Kepler)
Planetary Transits

Planet Finding Methods
NASA’s Kepler Mission
Planet Formation
Planet Formation

Planet Properties
Planet Formation

Planet Properties

System Properties
The Value of Transiting Planets
(among other things)

• Measurement of orbital inclination (mass)
The Value of Transiting Planets
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- Measurement of orbital inclination (mass)
- Measurement of the planet size (density)
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(among other things)

- Measurement of orbital inclination (mass)
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- Precision of orbital phase $\sim 0.0001$ (dynamics)
- Measurement of orbital obliquity (environment and history)
Dynamics with Transiting Planets

Transit Timing Variations

Transit times are equally spaced.

Agol, Steffen, Sari, Clarkson (2005), Holman and Murray (2005)
Dynamics with Transiting Planets

Transit Timing Variations

Unknown perturbing planet

Known transiting planet

Transit times are NOT equally spaced.

Agol, Steffen, Sari, Clarkson (2005), Holman and Murray (2005)
Transit Timing Variations

15 Minutes

Deviations from a constant orbital period

Time
Ford et al. (2012a), Steffen et al. (2012a), Fabrycky et al. (2012a), Steffen et al. (2013a), Xie (2012)
Planetary System Characterization
Systems with a Hot Jupiter
These planets are hard to form in situ. Some movement is necessary.
An issue in the Solar System
Discoveries of TNOs show an excess of objects near mean-motion resonance with Neptune.
Discoveries of TNOs show an excess of objects near mean-motion resonance with Neptune.
A Signature of Disk Migration

Mutually migrating bodies become trapped in mean-motion resonance

![Graph showing Log Orbital Distance vs. Time]
The movement of Hot Jupiters

Peace and Harmony
The movement of Hot Jupiters

Peace and Harmony

Violence and Mayhem
The movement of Hot Jupiters

Peace and Harmony

Violence and Mayhem
63 Hot Jupiter Systems from Kepler

Steffen et al. (2012)
Kepler Singles

![Graph showing Kepler Singles]
Kepler Singles and Multis

![Graph showing Kepler Singles and Multis with the x-axis representing Orbital Period (days) and the y-axis representing Planet Radius (Earth).]
Kepler’s Hot Jupiter Systems

• No evidence for additional transiting planets
Kepler’s Hot Jupiter Systems

- No evidence for additional transiting planets
- No evidence for companions from TTVs
Kepler’s Hot Jupiter Systems

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• Observed multiplanet systems in adjacent samples
• Observed TTV signals in adjacent samples
Kepler’s Hot Jupiter Systems

• No evidence for additional transiting planets
• No evidence for companions from TTVs
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• Observed multiplanet systems in adjacent samples
• Observed TTV signals in adjacent samples

• Hot Jupiters are lonely – Violence and Mayhem likely cause
All Kepler Candidates

![Graph showing the relationship between Planet Radius (Earth) and Orbital Period (days) for all Kepler candidates.](image-url)
All Kepler Candidates

Planet Radius (Earth) vs. Orbital Period (days)
How the other 99% live
Architectures of Multiplanet Systems

Distribution of orbital period ratios

Figure 4. Period ratio statistics of all planet pairs. Panel (a): Histogram of all period ratios in the sample (i.e. pairwise between all planets in higher order multiples, not just adjacent planets), out to a period ratio of 4. First order (top row) and second order (lower row) resonances are marked. The mode of the full distribution is just wide of the 3:2 resonance, and there is an asymmetric feature near the 2:1 resonance. There is a sharp cut-off interior to the 5:4 resonance. Panel (b): Planetary radii versus the period ratio for planetary pairs near ($P < 0.06 P_{the3 : 2$ resonance. Both radii of each pair plotted. Panel (c): same as panel b, but near ($P < 0.06 P_{the2 : 1$ resonance. Triangles denote planet pairs that are not adjacent, which have an intervening transiting planet.

Figures 5.

Distribution of $\phi_1$, a variable describing the set from first-order resonances (eq. 7), for all planetary pairs in the neighborhood of a first-order resonance, i.e. with a period ratio between 1 and 2.5. The spike between $0.1$ and $0.2$ means that period ratios just wide of first-order resonances are overpopulated relative to random.

Distribu&on 0f orbital period ra&os

N

(a)

Fabrycky et al. (2014)
Architectures of Multiplanet Systems

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Fabrycky et al. (2014)
Corrected Distribution of Period Ratios

Corrected for geometric alignment and pipeline completeness
Corrected Distribution of Period Ratios

Corrected for geometric alignment and pipeline completeness
Planets in a gas disk

Period Ratio vs. Orbits

- 0.01 Jupiter
- 0.03 Jupiter
- 0.1 Jupiter
- 0.3 Jupiter
- 1 Jupiter

Emily Ellinger Northwestern
Planets in a gas disk
(0.1 Jupiter)
Planets in a gas disk  
(1 Jupiter)
Architecture as a Function of Size

Figure 2 contains 20 points from the Q8 catalog—

Circles are from Q8

Small dots are from Q12

Large dots are Kepler-42

Line is:

$$\mathcal{P} \equiv \frac{P_2}{P_1} \gtrsim 2.3 (P_1/\text{day})^{-2/3}$$

Steffen & Farr (2013c)
1. Introduction

A lack of short-period multiplanet systems with close-proximity has been observed. These systems are often observed as hot Jupiters, which have orbital periods less than a few days. The relative isolation of these systems suggests that the primary planet in the system is likely to be the only planet of its kind. The mass of the host star is also a factor in the formation of these systems. The inner planet multiplicities are compared with the period ratio of 2.3(P_1/day)^{-2/3} given in the analysis. The line in the graph represents this period ratio. Theircles are from Q8, small dots are from Q12, and large dots are Kepler-42.
Predict 17.5 ± 5 planet pairs below the dashed line.

Observe two such pairs ($p \approx 0.001$), both in the same system.
Architecture as a Function of Size

Predict 17.5 ± 5 planet pairs below the dashed line.

Observe two such pairs \( p \approx 0.001 \), both in the same system.

Some additional physics must be included to explain this feature.

Steffen & Farr (2013c)
Kepler 42, Jupiter, and Mercury

Kepler 42

Jupiter and Galilean moons
Kepler 42, Jupiter, and Mercury

Kepler 42

Jupiter and Galilean moons

Kepler 42d

Mercury
Physics Beyond the Standard Model

Relativity
Physics Beyond the Standard Model

Relativity

Tides
Physics Beyond the Standard Model

Relativity

Tides

Magnetic Fields
Most systems are consistent with high multiplicity and missing planets.
Architecture of Kepler Systems

• Most systems are consistent with high multiplicity and missing planets

• While most planet pairs are not near MMR, many are
  • Some MMRs are very close (e.g. 7:6)
Architecture of Kepler Systems

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• There is “physics beyond the standard model” as orbital periods decrease
Architecture of Kepler Systems

- Most systems are consistent with high multiplicity and missing planets

- While most planet pairs are not near MMR, many are
  - Some MMRs are very close (e.g. 7:6)

- There is “physics beyond the standard model” as orbital periods decrease

- Significant excess of planet pairs near a period ratio of 2.2 (Not a ratio one would naturally predict.)
Whole System Architectures
Whole System Architectures

Limitations of Kepler:
  • Sensitivity falls off rapidly for P > 400 days
  • Mutual inclinations prevent many detections
  • Dim targets limit supplementary observations
Whole System Architectures

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NASA’s TESS Mission
Whole System Architectures

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Advantages of TESS:
- 400x the survey area
- Stars are 100x brighter, 10x closer
- Wide variety of supplementary observations
- 1-minute cadence and 30-minute full-frame images
Whole System Architectures

Limitations of Kepler:

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Advantages of TESS:

• 400x the survey area
• Stars are 100x brighter, 10x closer
• Wide variety of supplementary observations
• 1-minute cadence and 30-minute full-frame images

However:

• Most stars observed for only 30 days
Definitive Astrometry Detections to Date
Predicted Astrometry Detections from GAIA

Fig. 2.— Histograms of the predicted planet detections with Gaia, for $d > 2$ pc, a function of: (a) $G$ magnitude; (b) distance $d$; and (c) planet mass $M_p$, where the rising distribution up to the adopted occurrence threshold of $15 M_J$ contrasts with the mass distribution for the simulated planets (d, which is a $1$ in $10^4$ resampling of the simulated planet distribution, showing the $M_p^{1.31}$ power-law behaviour as the dashed line); (e) semi-major axis $a$; (f) eccentricity $e$.  

Perryman, Hartman, & Bakos (2014)
Planets observable with Sphere and GPI (2013-)

Nearby stars (<20 pc)

Young stars (<$5 \times 10^8$ yrs)

⇒ Tens of young giant planets at rather large separations
Planets observable with Sphere and GPI (2013-)

Nearby stars (<20 pc)

Young stars (<5 \(10^8\) yrs)

➤ Tens of young giant planets at rather large separations

Slide stolen from R. Gratton
Simulated Planets within 30 pc

The dashed circle indicates the approximate area of WFIRST-AFTA coronagraph sensitivity.

- Giant planets
- Rocky planets
- Water/ice planets
- Known Doppler planets

Contrast vs. Separation (arcsec)

Macintosh & Savransky
Kepler-consistent RF; 1.9 pl/star
Main sequence non binary stars

04/30/2014
TESS A & D Working Group

Measurement and Interpretation of Whole System Architectures

- Coordinate Transit, RV, Astrometry, Direct Imaging measurements
- Identify additional planets at a wide range of periods
- Constrain additional planets at a wide range of periods
- Measure orbital eccentricity and inclinations
- Interpret results in terms of formation and dynamical evolution
- Measure ephemerides to predict transits
What now?

- Only $\epsilon$ of the science has been done on the Kepler data
- New pipeline and vetting processes being completed
What now?

• Only $\varepsilon$ of the science has been done on the Kepler data
• New pipeline and vetting processes being completed

• Continue the analysis of existing data, now through Quarter 17
• Understand the cause of the observed anomalies
• Prepare for anticipated data from planned missions
What now?
Planet Properties with Kepler

Kepler-36
Carter, Agol, et al. 2011

Kepler-11
Lissauer et al. (2013)
Architectures of Multiplanet Systems

"Stacking" the first-order resonances

\[ \zeta_1 = 3 \left( \frac{1}{P - 1} - \text{Round} \left[ \frac{1}{P - 1} \right] \right) \]

Fabrycky et al. (2012)
Effects to Consider

Pipeline Completeness

Geometric Transit Probability
Modified Kernel Density Estimate

\[ D_{\text{obs}}(P) \propto \beta_{\text{geo}} \beta_{\text{pipe}} D_{\text{true}}(P) \]

\[ \beta = \frac{P_2(P)}{P_2(1)} \]
Combined Corrections
A Thought Experiment

Suppose that this system is fundamentally the same as this system.
Suppose that this system is fundamentally the same as this system.

Except that the planets happen to have slightly different mutual inclinations.
Period Ratio Distribution of Adjacent Pairs

Systems with four or more planets.

Steffen (2013b)
Period Ratio Distribution of Adjacent Pairs

Systems with four or more planets.

Excess near the 3:2 MMR

Fiducial distribution model (truncated Rayleigh)

Steffen (2013b)
Period Ratio Distribution of Adjacent Pairs

Steffen (2013b)
Period Ratio Distribution of Adjacent Pairs

Steffen (2013b)

2 planets

4+ planets

3 planets
Period Ratio Distribution of Adjacent Pairs

Steffen (2013b)

2 planets

3 planets

4+ planets
Period Ratio Distribution of Adjacent Pairs

Steffen (2013b)

4+ planets

2 planets

3 planets
Period Ratio Distribution of Adjacent Pairs

Steffen (2013b)

2 planets

3 planets

4+ planets
Analysis of Kepler’s Hot Jupiters

We choose our boundaries for the planet sizes by first selecting all planet candidates with orbital periods between $p$ and $p_0$ days. See Figure 1. We see a transition from Jupiter size objects to the much larger population of Neptune and smaller objects in the distribution of candidate sizes and choose hot Jupiter candidates with sizes between $r_{\text{Jup}}$ and $r_{\text{m}}$. The number of KOIs that satisfy the above selection criteria is $u_k$ and they constitute our hot Jupiter sample. We note that uncertainties in the stellar radii may produce systematic bias or uncertainty in these candidate sizes.

In addition to the sample of hot Jupiters, we consider two neighboring samples of KOIs specifically hot Neptunes and warm Jupiters. For the hot Neptunes, we select all KOIs with sizes between $r_{\text{m}}$ and $r_{\text{q}}$ and periods between $p_{\text{w}}$ and $p_{\text{r}}$ days. The warm Jupiters satisfy the same size criteria as the hot Jupiters but have periods between $p_{\text{r}}$ and $p_{\text{t}}$ days. These cuts yield $q_q$ hot Neptunes and $q_w$ warm Jupiters. In each of these samples, there is one system that we ignore as they are missing several quarters of data. Also, KOI $x_k$ is a known triple star system involving an eclipsing binary. Steffen et al. PNAS (2012b)

Steffen et al. PNAS (2012b)
Distribution Tail

$\left( \frac{P_2}{P_1} \right)^{-1.26 \pm 0.05}$
What now?

- Much Kepler data remains to be studied
  - Only ½ of the data were analyzed in the most recent catalog
  - Only ε of the science has been done on those data
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![Graph showing planet mass and radius relationships](image)
What now?

- Much Kepler data remains to be studied
- Only ½ of the data were analyzed in the most recent catalog
- Only ε of the science has been done on those data
What now?

- Much Kepler data remains to be studied
  - Only $\frac{1}{2}$ of the data were analyzed in the most recent catalog
  - Only $\varepsilon$ of the science has been done on those data
What now?

• Much Kepler data remains to be studied
  • Only ½ of the data were analyzed in the most recent catalog
  • Only ε of the science has been done on those data
Some possibilities being pursued

Hwang, Steffen, & Rasio (in prep)
Some possibilities being pursued

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TTVs for Planet Characterization

Kepler 11

Lissauer et al. (2011)
TTVs for Planet Characterization

Kepler 11

Kepler 36

Lissauer et al. (2011)

Carter, Agol, et al. (2012)
TTVs for Planet Characterization

The mass–radius curve at the composition (H/He, GJ 1214 b, and GJ 3470 b. Solar system planets Venus and Uranus are shown by open squares; in order of increasing radius, these are CoRoT-7 b, 55 Cancre each planet. Other known exoplanets in this mass and radius range are shown by circles, filled for Kepler-11, open for others, with numbers and letters indicating their incident bolometric flux that they receive.

Updated mass–radius diagram for transiting exoplanets with measured masses up to 100 M⊕. In addition, we have included an updated version of the mass-loss threshold diagram presented in Lopez et al. (2013). Bolometric flux at the top of the atmosphere, relative to the flux incident on Earth, is plotted against the product of planet mass and planet density. Again, the critical mass-loss timescale found by Lopez et al. (2012) models. Potentially rocky planets are rust colored. The dashed black line shows the uncertainties on the albedo and the iron fraction of the rocky planet’s mass, radius, incident flux, and age as well as theoretical models. For b, approximately half of the observed radius is due to its H/He envelope. The cores make up 46%, 54%, 40%, and 48% of the total radii of planets Kepler-11 c, d, e, and f, respectively, and thus only 6%–16% of the volume. Moreover, even for Kepler-11 b, the rocky core only makes up 66% of the total mass, and thus only 6%–16% of the volume. Of the total radii of planets Kepler-11 c, d, e, and f, respectively, 25%, 35%, 30%, and 39% is contributed by the H/He envelopes at 8 Gyr; each one is tailored to certain compositions.

The solid blue curve is for 100% water by mass, and the solid orange curve is for 50% water by mass. The solid blue curve is for a pure water composition the same as that of the bulk Earth. The dashed blue curve is for 50% water by mass, and the dashed orange curve is for 25% water by mass. The dotted orange curves are for H/He molecular fluid phases, with the ionic fluid and plasma pressure ice phases. Most of the H/He envelopes at 8 Gyr; each one is tailored to certain compositions.

For 50% water by mass, and the solid blue curve is for a pure H/He composition the same as that of the bulk Earth. The dashed blue curve is for 50% water by mass, and the dashed orange curve is for 25% water by mass. The dotted orange curves are for H/He molecular fluid phases, with the ionic fluid and plasma pressure ice phases. Most of the H/He envelopes at 8 Gyr; each one is tailored to certain compositions. Planets are color-coded by the incident bolometric flux that they receive.

Figure 9. The Astrophysical Journal (A color version of this figure is available in the online journal.)

Lissauer et al. (2013)
TTVs for Planet Characterization

• TTVs can measure the masses of planets that are too small to measure with RV observations
TTVs for Planet Characterization

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• Most of the Kepler planets have masses and sizes that are not present in our solar system
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• Many Kepler planets are much closer together than planets in the solar system
TTVs for Planet Characterization

• TTVs can measure the masses of planets that are too small to measure with RV observations

• Most of the Kepler planets have masses and sizes that are not present in our solar system

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• Planets seen by Kepler are well inside the “snow line” which planet formation theories must address
Multibody/TTV Working Group

Jack Lissauer (chair), Jason Steffen (chair), Eric Agol, Dan Fabrycky, Eric Ford, Tsevi Mazeh, Jerry Orosz, Darin Ragozzine, Jason Rowe, William Welsh
Mulbody/TTV Working Group

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Kepler 9: First definitive TTV signal

\[ O - C_{\text{linear}} \text{ (min)} \]

\[ t \text{ (BJD) } - 2454900 \]

- \( \times \) planet b
- \( \bullet \) planet c

Holman et al. 2010
TTVs for planet confirmation

Candidate | Planet

Show from TTVs that two planets must be in the same system.

Steffen et al. (2012a), Steffen et al. (2013a)
TTVs for planet confirmation

Candidate → Planet

Show from TTVs that two planets must be in the same system.

Show that their masses are planetary by requiring orbital stability.

Steffen et al. (2012a), Steffen et al. (2013a)
Kepler Planet Candidates through Q8
Kepler Planet Candidates through Q8

> 450 multi-planet systems
Different planet populations

Numbers of multiplanets:
115 doubles, 45 triples, 8 quads,
1 & 1 of five and six

Lissauer et al. 2011
Multiple Candidate Systems

Fabrycky et al. 2012
Multi-transiting Systems

FIVE KEPLER TARGET STARS THAT SHOW MULTIPLE TRANSITING EXOPLANET CANDIDATES


Systems with multiple transiting planets are significantly easier to interpret.
Large TTVs required the development of a new search algorithm. These two planets are very near the 7:6 mean-motion resonance—their orbital distances are 10% different. Their densities differ by nearly a factor of 10.

Deck et al (2012) showed that this system undergoes short-term dynamical chaos.

How do you make such a system?

Good question.

Carter, Agol, et al. 2011
Signature of Violence and Mayhem (Rossiter-McLaughlin Effect)

Approaching side is blueshifted

Receding side is blueshifted
For tidal dissipation are not understood (i.e. the and it is not observed in the Sun. For further discussion, see Winn invoke core-envelope decoupling, but it is unclear why the coupling would be so weak, high obliquities are also those with the longest orbital periods, leading to exceptionally to realign with the orbit, and this occurs preferentially for low-mass stars because of their

Regardless of the explanation, recent observations have strengthened the evidence for

To illustrate this point, Figure 5 shows the RM results as a function of a dimensionless parameter that characterizes the expected timescale for tidal dissipation, 100

Radial velocity [m s⁻¹]

Relative flux

Time [hr]

Radial velocity [m s⁻¹]

HD 189733

HAT–P–7

\( \lambda = -1.4° \pm 1.1° \)

\( \lambda = 182.5° \pm 9.4° \)

\( \lambda = 37.3° \pm 3.7° \)

\( \lambda = 182.5° \pm 9.4° \).
Kepler’s Planet Candidates
22 Months: May 2009 - Mar 2011

Radius Relative to Earth

Orbital Period in days

Chris Burke:
216.02
Migration Changes System Architecture

Studying the dynamics of a system today tells us about its history and gives insight into the formation of the system.
Large TTVs required the development of a new search algorithm.

These two planets are very near the 7:6 mean-motion resonance—their orbital distances are 10% different.
Kepler 36
Self Similarity Test

Outline is the period ratio distribution for the outer two planets.

Solid is the period ratio distribution for the inner two planets.
Orbital Architectures with Transiting Planets

Inclination and Multiplicity

Fang and Margot (2012)

Lissauer et al (2011)

Figure 5. Same as Figure 3, except this diagram shows combined (multiplied) probabilities from $\chi^2$ and K-S tests. These probabilities represent the overall goodness of fit of various models to the Kepler sample. (A color version of this figure is available in the online journal.)

4.2. Effects of False Positives and Search Incompleteness

The results of our study do not take into account the existence of false positives that mimic real planet transit signals in the KOI data set. For the Kepler sample released by Borucki et al. (2011b), Morton & Johnson (2011) estimated that false positive probabilities were generally low at $\lesssim 10\%$, and an analysis using binary statistics by Lissauer et al. (2012) estimated that $\sim 98\%$ of the multi-planet systems are real. For the latest Kepler sample released by Batalha et al. (2012), Fabrycky et al. (2012) discussed how $\sim 96\%$ of pairs in multi-transiting candidate systems are likely to be real planets using stability arguments. For the purposes of our study, we assumed that all planetary candidates are real. We expect that the existence of false positives can potentially affect the fit between multiplicity vectors (e.g., Table 1), particularly for the case of singly transiting systems where the actual population may actually have lower numbers than reported due to false positives. We do not expect that false positives will significantly influence the fit between normalized transit duration ratios (e.g., Figure 7) since such ratios are only computed for multi-planet systems, which we expect to be a higher-fidelity sample than singly transiting systems.

To determine the effect of false positives on our results, we repeated the entire analysis described in this paper for two cases. In the first case, we removed all false positives described in the literature (Howard et al. 2012; Batalha et al. 2012; Fabrycky et al. 2012; Sartoretti et al. 2012; Ofir & Dreizler 2012; Colin et al. 2012); a total of 35 false positives were removed from 10

Fang & Margot (2012)
Orbital Architectures with Transiting Planets

Inclination and Multiplicity

Fang and Margot (2012)  
Lissauer et al (2011)

Size Ratios

Ciardi et al. (2013)
Orbital Architectures with Transiting Planets

Inclination and Multiplicity
Fang and Margot (2012)

Lissauer et al (2011)

Size Ratios
Ciardi et al. (2013)

Period Ratios
Fabrycky et al. (2012)
Analysis of Transiting Hot Jupiter Systems

Look for transiting companions...

Steffen et al. PNAS (2013)
Analysis of Transiting Hot Jupiter Systems

Look for transiting companions...

Consider mutual inclinations...

Steffen et al. PNAS (2013)
Analysis of Transiting Hot Jupiter Systems

Look for transiting companions...

Look for TTVs in both hot Jupiter and super Earth systems

Consider mutual inclinations...

Steffen et al. PNAS (2013)
Subsets of the Period Ratio Distribution

- Two planet systems vs. inner pair of larger systems ($p \approx 0.0003$)

- Self similarity in systems with three or more planets ($p \approx 0.05$)

- Test systems with short and long orbital periods ($p \approx 0.01$ for 3+ planets)
Some possibilities being pursued

Most Kepler multiplanet systems are dynamically packed. There is not much wiggle room.

Perhaps some have gone unstable and had subsequent collisions.

( PRELIMINARY ) Period ratio distribution for unstable Kepler-11 systems.
TTVs for Planet Characterization

Kepler 11

Lissauer et al. 2011
Not from a lack of planets

Orbital period distribution of singles (shaded) and multis (outline).

Statistical significance of the difference between the two distributions.

The excess of short-period planets in single-planet systems may be analogous to the hot Jupiters.
Planetary Transits

Planet Finding Methods

Jupiter: 1 part per 1000

Earth: 1 part per 100,000
Kepler Spacecraft

- 95 cm Schmidt Corrector (Fused Silica)
- Focal Plane Radiator
- 1.4m Primary Mirror
- Focal Plane w/ 42 Science CCD’s & 4 Fine Guidance Sensors
Kepler Photometer

50 micromagnitudes in 6 hours
30 minute cadence

Continuously monitor ~150,000 target stars

Images are de-focused

Only target pixels are sent back to Earth
Kepler Field of View

~100 square degrees

First light image
What now?

• Much Kepler data remains to be studied
  • Only ½ of the data were analyzed in the most recent catalog
  • Only ε of the science has been done on those data

• Flesh out the mass radius relationship at the transition from sub-Neptunes to super-Earths

• Understand the cause of the missing planet pairs at short orbital periods

• Understand the cause of the architectures for 2 planet, 3 planet, and 4+ planet systems
  • Why does mean-motion resonance depend on multiplicity?
Subsets of the Period Ratio Distribution

Do the inner pair of 4+ systems match 2 planet systems?

Steffen (2013b)
Subsets of the Period Ratio Distribution

Do the inner pair of 4+ systems match 2 planet systems?

Steffen (2013b)
Subsets of the Period Ratio Distribution

Do the inner pair of 4+ systems match 2 planet systems?

Are systems self-similar?

Steffen (2013b)
Subsets of the Period Ratio Distribution

Do the inner pair of 4+ systems match 2 planet systems?

Are systems self-similar?

Are small systems the same as large systems?

Steffen (2013b)
of the five Kepler-11 planets whose mass has been measured, we rock and 1 by black letters. The solid black curve is for an Earth-like composition with 2 by open squares; in order of increasing radius, these are CoRoT-7 b, 55 Cancre circles, filled for Kepler-11, open for others, with numbers and letters indicating by the incident bolometric flux that they receive.

Figure 9. The Astrophysical Journal (A color version of this figure is available in the online journal.)

Table 4

<table>
<thead>
<tr>
<th>Planet</th>
<th>Mass (M⊕)</th>
<th>Radius (R⊕)</th>
<th>H/He</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kepler-11 b</td>
<td>1.9 ± 0.2</td>
<td>1.28 ± 0.06</td>
<td>5%</td>
</tr>
<tr>
<td>Kepler-11 c</td>
<td>0.8 ± 0.1</td>
<td>0.66 ± 0.03</td>
<td>0.5%</td>
</tr>
<tr>
<td>Kepler-11 d</td>
<td>2.49 ± 0.05</td>
<td>1.72 ± 0.09</td>
<td>6.6%</td>
</tr>
<tr>
<td>Kepler-11 e</td>
<td>3.26 ± 0.06</td>
<td>2.9 ± 0.08</td>
<td>15.1%</td>
</tr>
</tbody>
</table>

Notes.

- The new masses imply that Kepler-11 c is less massive than if it were composed of pure water, meaning that it must have a large He envelope. However, Kepler-11 b can still be explained by He or a steam envelope on top of a rocky core. If we

- The cores make up 46%, 54%, 40%, and 48% of their mass in their H/He envelopes, Kepler-11 c is 5%, 1%, and 2% of the volume. Moreover, even for every Kepler-11 planet whose mass has been measured except Kepler-11 d is 6%,—16% of the volume. Moreover, even for every Kepler-11 planet whose mass has been measured except Kepler-11 d is 6%–16% of the volume. Moreover, even for Kepler-11 planet's mass, radius, incident flux, and age as well as theoretical models. Potentially rocky planets are rust colored. The dashed black line shows of their mass in their H/He envelopes, is plotted against the product of planet mass and planet density. Again, (A color version of this figure is available in the online journal.)

- We estimate the percentage of water by mass. The envelope of the observed radius is due to its high-pressure ice phases. Most of the H is far too irradiated for their interiors to include liquid or high-temperature ice phases. The new mass-loss threshold diagram from Lopez et al. (2012) shows that we estimate the percentage of water by mass. The envelope of the observed radius is due to its high-pressure ice phases. Most of the H is far too irradiated for their interiors to include liquid or high-temperature ice phases.
Updated version of the mass-loss threshold diagram from Lopez et al. (2012). Bolometric flux at the top of the atmosphere, relative to the flux incident on the planet (Fp/F⊙) and thus only 6%–16% of the volume. Moreover, even for rocks, the mass of the core is 46% of the mass.

For mixtures of rock with H2O, assume that Kepler-11 b's envelope is water rather than H2. We find that Kepler-11 b is far too irradiated for its interiors to include liquid or high-pressure ice, and thus only 6%–16% of the volume. Moreover, even for a planet like Kepler-11 b, which is mostly composed of steam, since planets like Kepler-11 b are far too irradiated for their interiors to include liquid or high-pressure ice.

In addition, we have included an updated version of the mass–radius curve at the composition of the five Kepler-11 planets whose mass has been measured, we find that Kepler-11 planets are shown by filled circles. The open squares show the planet's mass, radius, incident flux, and age as well as theoretical predictions.

The new masses imply that Kepler-11 c is less massive than if it were composed of pure water, meaning that it must have a large H2O/He envelope at 8 Gyr; each one is tailored to match a Kepler-11 planet and is computed at the appropriate flux for that planet. The mass and eccentricity of Kepler-11 g are ±0.011, ±0.007. Planets are color-coded by the percentage mass fraction and incident flux of that planet.

Notes.

Updated mass–radius diagram for transiting exoplanets with measured masses up to 100% water compositions. In addition, for each planet's mass, radius, incident flux, and age as well as theoretical predictions.

Table 3. Updated mass–radius diagram for transiting exoplanets with measured masses up to 100% water compositions. In addition, for each planet, the adopted mass and radius uncertainties (Lissauer et al. 2010) are quoted uncertainties include the measured uncertainties on each planet's mass, radius, incident flux, and age as well as theoretical predictions.

The mass and eccentricity of Kepler-11 g are ±0.011, ±0.007. Planets are color-coded by the percentage mass fraction and incident flux of that planet.
Early searches for a TTV signal

TrES-1

HD 209458

Eccentricity

Period Ratio

Eccentricity

Period Ratio

Steffen & Agol (2005)

Agol & Steffen (2007)
Not from a lack of planets

Period distribution of singles (shaded) and multis (outline)

The excess of short-period planets in single-planet systems may be analogous to the hot Jupiters.

Steffen & Farr (2013c)
Planet Finding Methods

Astrometry
Planet Finding Methods

Direct Imaging
Planet Finding Methods

Direct Imaging
Planet Finding Methods

Radial Velocity (Doppler)
Expected TESS exoplanet yield

- **EARTHS & SUPER-EARTHS:** 315
- **SUB-NEPTUNES:** 710
- **NEPTUNES:** 1060
- **JUPITERS:** 660
Expected TESS exoplanet yield

RV follow-up is dedicated to measuring small planet masses.
WFIRST-AFTA Brings Humanity Closer to Characterizing Earths

- WFIRST-AFTA advances many of the key elements needed for a coronagraph to image Earth
  - Coronagraph
  - Wavefront sensing & control
  - Detectors
  - Algorithms
Figure 4. Period ratio statistics of all planet pairs. Panel (a): Histogram of all period ratios in the sample (i.e. pairwise between all planets in higher order multiples, not just adjacent planets), out to a period ratio of 4. First order (top row) and second order (lower row) resonances are marked. The mode of the full distribution is just wide of the 3:2 resonance, and there is an asymmetric feature near the 2:1 resonance. There is a sharp cut-off interior to the 5:4 resonance. Panel (b): Planetary radii versus the period ratio for planetary pairs near $(P < 0.06 P_*)$ the 3:2 resonance. Both radii of each pair plotted. Panel (c): same as panel b, but near $(P < 0.06 P_*)$ the 2:1 resonance. Triangles denote planet pairs that are not adjacent, which have an intervening transiting planet.

Let us explore this preference for first-order resonances more. First, we compare the observed $|\gamma_1|$ distribution to a random distribution solely around the neighborhood of 2:1 (between 7:4 and 5:2) alone. The distributions significantly differ, with a p-value of 0.029, however this has weakened from 0.00099 (in Paper I) with the expanded sample including more small planets. The more important resonance contributing to the first-order resonance result is that systems in the neighborhood of 3:2 (between 10:7 and 8:5) tend to be near 3:2; $|\gamma_1|$ differs from a random distribution with a p-value of 0.0046. Looking back at panel a of figure 4, the global peak is just wide of the 3:2 resonance; a smaller peak exists just wide of 2:1. The peak at 3:2 appears to be a pile-up, in the sense that the spike is an excess on top of a baseline. The peak just wide of 2:1 contains only slightly more pairs than the trough just narrow of 2:1 is missing; this feature may imply an evolutionary "redistribution" determines this distribution more than a "pile-up" at the formation epoch. For a better view of these resonances, we plot scatter plots near these resonances in panels b and c of figure 4.

Figure 5. Histogram of $\gamma_1$, a variable describing the set from first-order resonances (eq. 7), for all planetary pairs in the neighborhood of a first-order resonance, i.e. with a period ratio between 1 and 2.5. The spike between 0.1 and 0.2 means that period ratios just wide of first-order resonances are overpopulated relative to random.
Figure 4.

Panel (a): Histogram of all period ratios in the sample (i.e. pairwise between all planets in higher order multiples, not just adjacent planets), out to a period ratio of 4. First order (top row) and second order (lower row) resonances are marked. The mode of the full distribution is just wide of the 3:2 resonance, and there is an asymmetric feature near the 2:1 resonance. There is a sharp cut-off interior to the 5:4 resonance.

Panel (b): Planetary radii versus the period ratio for planetary pairs near \( P < 0.06 \) through the 3:2 resonance. Both radii of each planet pair plotted. Panel (c): same as panel b, but near \( P < 0.06 \) through the 2:1 resonance. Triangles denote planet pairs that are not adjacent, which have an intervening transiting planet.

Figure 5.

Histogram of \( \beta \), a variable describing the set from first-order resonances (eq. 7), for all planetary pairs in the neighborhood of a first-order resonance, i.e. with a period ratio between 1 and 2.5. The spike between 0.1 and 0.2 means that period ratios just wide of first-order resonances are overpopulated relative to random.

Let us explore this preference for first-order resonances more. First, we compare the observed \( |\beta| \) distribution to a random distribution solely around the neighborhood of 2:1 (between 7:4 and 5:2) alone. The distributions significantly differ, with a p-value of 0.029, however this has weakened from 0.00099 (in Paper I) with the expanded sample including more small planets. The more important resonance contributing to the first-order resonance result is that systems in the neighborhood of 3:2 (between 10:7 and 8:5) tend to be near 3:2; \( |\beta| \) differs from a random distribution with a p-value of 0.0046. Looking back at panel a of figure 4, the global peak is just wide of the 3:2 resonance; a smaller peak exists just wide of 2:1. The peak at 3:2 appears to be a pile-up, in the sense that the spike is an excess on top of a baseline. The peak just wide of 2:1 contains only slightly more pairs than the trough just narrow of 2:1 is missing; this feature may imply an evolutionary “redistribution” determines this distribution more than a “pile-up” at the formation epoch. For a better view of these resonances, we plot scatter plots near these resonances in panels b and c of figure 4.

1) Correct for geometric alignment
2) Correct for pipeline completeness
Architecture of Kepler

Figure 4. Period ratio statistics of all planet pairs. Panel (a): Histogram of all period ratios in the sample (i.e. pairwise between all planets in higher order multiples, not just adjacent planets), out to a period ratio of 4. First order (top row) and second order (lower row) resonances are marked. The mode of the full distribution is just wide of the 3:2 resonance, and there is an asymmetric feature near the 2:1 resonance. There is a sharp cut-off interior to the 5:4 resonance. Panel (b): Planetary radii versus the period ratio for planetary pairs near ($P < 0.06 \times$). Both radii are plotted. Panel (c): same as panel b, but near ($P < 0.06 \times$) the 2:1 resonance. Triangles denote planet pairs that are not adjacent, which have an intervening transiting planet.

Figure 5. Corrected distribution of period ratios in the neighborhood of first-order resonances (eq. 7), for all planetary pairs in the neighborhood of a first-order resonance, i.e. with a period ratio between 1 and 2.5. The spike between 0.1 and 0.2 means that period ratios just wide of first-order resonances are overpopulated relative to random. The peak at 3:2 appears to be a pile-up, in the sense that the spike is an excess on top of a baseline. The peak just wide of 2:1 contains only slightly more pairs than the trough just narrow of 2:1 is missing; this feature may imply an evolutionary "redistribution" determines this distribution more than a "pile-up" at the formation epoch. For a better view of these resonances, we plot scatter plots near these resonances in panels b and c of figure 4.
Architecture of Kepler Systems

- Most systems are consistent with high multiplicity and missing planets
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  - Some MMRs are very close (e.g. 7:6)
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Architecture of Kepler Systems

• Most systems are consistent with high multiplicity and missing planets

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• Some changes in system architecture with planet multiplicity—difference in formation or dynamical evolution

• There is “physics beyond the standard model” as orbital periods decrease

• Significant excess of planet pairs near a period ratio of 2.2 (Not a ratio one would naturally predict.)