New Views of Exoplanets from NASA’s *Kepler* mission

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University of Chicago
Planets are common

Transits/Kepler

Doppler/HARPS

(Petigura, Howard, Marcy 2013)

(Mayor et al. 2011)

…and small planets are the most common
Solar System properties

- Rocky planets in close (<2 AU)
- Gas giant planets where volatile compounds could solidify (5.2, 9.5 AU)
- “Ice” giant planets in the outskirts (19, 30 AU)
- Low eccentricities (mostly <0.1)
- Flat relative to each other (~2 degrees of tilt)
- No orbital resonances
Kepler Mission
(NASA, 2009-2013*)

resurrection being planned

• A search for Earth-like planets in transit
• Photometry of 150,000 stars
• ~20 ppm in 6 hours; 30 minute cadence
• In heliocentric orbit
The Kepler Orrery III

$t[BJD] = 2455215$

http://www.youtube.com/watch?v=gnZVvYm6KKM
715 Newly Verified Planets More Than Triples the Number of Confirmed Kepler Planets -- 2/26/14
715 Newly Verified Planets Means *Kepler* has found the majority of Exoplanets (961 of ~1790)
Note coplanarity!
Full architectures of Exoplanetary Systems?

Basic facts:
- Planet number
- Masses
- Radii

Dynamical properties:
- Periods (n.b.: their ratios)
- Eccentricities
- Mutual Inclinations

<table>
<thead>
<tr>
<th>Transits</th>
<th>Radial Velocities</th>
</tr>
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<tbody>
<tr>
<td>w/ TTV</td>
<td>✓</td>
</tr>
<tr>
<td>w/ TTV</td>
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</tbody>
</table>

TTV = Transit timing Variation

>~100 significant TTV cases: Mazeh et al. 2013)
Dynamics: Orbital Timescales
Dynamics: Resonant Orbits

$P_2/P_1 = 2.00$
KOI-806 = Kepler-30

Fabrycky, Ford, Steffen et al. 2012
KOI-806 = Kepler-30

Fabrycky, Ford, Steffen et al. 2012
Super-Earths and Mini-Neptunes

Kepler-11

Lissauer, Fabrycky, Ford et al. 2011
<table>
<thead>
<tr>
<th>Planet</th>
<th>KOI-351</th>
<th>KOI-351.06</th>
<th>KOI-351.05</th>
<th>KOI-351.03</th>
<th>KOI-351.04</th>
<th>KOI-351.07</th>
<th>KOI-351.02</th>
<th>KOI-351.01</th>
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<tbody>
<tr>
<td>KOI #</td>
<td>KOI-351</td>
<td>KOI-351.06</td>
<td>KOI-351.05</td>
<td>KOI-351.03</td>
<td>KOI-351.04</td>
<td>KOI-351.07</td>
<td>KOI-351.02</td>
<td>KOI-351.01</td>
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<tr>
<td>$T_0$</td>
<td>70.6797±</td>
<td>72.5208±</td>
<td>91.9622±</td>
<td>67.2952±</td>
<td>62.791±</td>
<td>79.8448±</td>
<td>73.4992±</td>
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<tr>
<td>(BJD-2454900)</td>
<td>0.0012</td>
<td>0.0038</td>
<td>0.0035</td>
<td>0.0079</td>
<td>0.011</td>
<td>0.0015</td>
<td>0.00085</td>
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<tr>
<td>$P$</td>
<td>7.008214±</td>
<td>8.71897±</td>
<td>59.7300±</td>
<td>91.9408±</td>
<td>124.9134±</td>
<td>216.70287±</td>
<td>331.5994±</td>
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<tr>
<td>[days]</td>
<td>0.000102</td>
<td>0.000324</td>
<td>0.00027</td>
<td>0.00078</td>
<td>0.0013</td>
<td>0.00037</td>
<td>0.00032</td>
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<tr>
<td>duration [hr]</td>
<td>3.72 ± 0.02</td>
<td>4.02 ± 0.02</td>
<td>7.90 ± 0.06</td>
<td>9.16 ± 0.08</td>
<td>10.03 ± 0.11</td>
<td>11.38 ± 0.06</td>
<td>13.21 ± 0.04</td>
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</tr>
<tr>
<td>depth [%]</td>
<td>0.0135 ± 0.0009</td>
<td>0.0175 ± 0.0009</td>
<td>0.0580 ± 0.0017</td>
<td>0.0502 ± 0.0019</td>
<td>0.0642 ± 0.0032</td>
<td>0.4225 ± 0.0028</td>
<td>0.8246 ± 0.0055</td>
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</tr>
<tr>
<td>$R_p/R_*$</td>
<td>0.0108 ± 0.0004</td>
<td>0.0122 ± 0.0003</td>
<td>0.0223 ± 0.0004</td>
<td>0.0208 ± 0.0004</td>
<td>0.0234 ± 0.0006</td>
<td>0.0605 ± 0.0005</td>
<td>0.0840 ± 0.0005</td>
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</tr>
<tr>
<td>$b$</td>
<td>0.02 ± 0.02</td>
<td>-0.00 ± 0.26</td>
<td>0.22 ± 0.13</td>
<td>0.01 ± 0.28</td>
<td>-0.00 ± 0.25</td>
<td>-0.01 ± 0.24</td>
<td>-0.04 ± 0.23</td>
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</tr>
<tr>
<td>$R_p$ [R$_\odot$]</td>
<td>1.37 ± 0.08</td>
<td>1.55 ± 0.09</td>
<td>2.83 ± 0.15</td>
<td>2.64 ± 0.14</td>
<td>2.98 ± 0.17</td>
<td>7.65 ± 0.38</td>
<td>10.69 ± 0.53</td>
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<tr>
<td>$S/S_\odot$</td>
<td>292.51 ± 23.27</td>
<td>217.55 ± 17.23</td>
<td>17.18 ± 1.58</td>
<td>9.61 ± 0.82</td>
<td>6.31 ± 0.52</td>
<td>3.17 ± 0.26</td>
<td>1.74 ± 0.15</td>
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</tr>
</tbody>
</table>
Planetary System
KOI-961

KOI-961.03
KOI-961.01
KOI-961.02

Red Dwarf Star
KOI-961

Star and orbits to scale, planets smaller than shown.

Muirhead, Johnson et al. 2012
KOI-730: Three Pairs of First-Order Resonances

<table>
<thead>
<tr>
<th>name</th>
<th>period (d)</th>
<th>$R_p$ ($R_E$)</th>
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<tbody>
<tr>
<td>730.04</td>
<td>7.3831</td>
<td>1.8</td>
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<tr>
<td>730.02</td>
<td>9.8499</td>
<td>2.1</td>
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<tr>
<td>730.01</td>
<td>14.7903</td>
<td>2.8</td>
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<tr>
<td>730.02</td>
<td>19.7216</td>
<td>2.4</td>
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</tbody>
</table>

$P/P=1.33411(8)$ 4:3
$P/P=1.50157(5)$ 3:2
$P/P=1.33341(3)$ 4:3

3:4:6:8

Kepler; Lissauer et al. 2011, Fabrycky et al. 2012
Disk Migration into Resonance
Gas giants can have giant eccentricities
Planet with Eccentricity, Being Kicked Still!

- KOI-1474 (Dawson et al. 2012, 2014)

Doppler confirmation of a TTV planet discovery.
Gas giants can have giant eccentricities...or hug their stars.
Eclipsing Binary Stars

- Primary Eclipse
- Secondary Eclipse

Diagram showing the brightness changes over time for an eclipsing binary system.
Kepler-16(AB)b

credit: Tim Pyle (NASA)

http://kepler.nasa.gov/multimedia/animations/artistsconcepts/?ImageID=166
⇒ 3.23 days, $M_{\text{sin}} = 1.13 \pm 0.09 \, M_{\text{earth}}$
⇒ 4 light years away!
⇒ In a triple stellar system
Filtered out binary motion, magnetic cycles, starspots; to be confirmed….
Circum-Binary Planets from Kepler

Alpha Centauri

PH1

The Economist
Diversity of Planetary Systems:

Yes, planets are also common outside the Solar System… but they are often…

a) Super-Massive Terrestrials
b) Mini-Neptunes with packed orbits
c) Orbits in resonant chains
d) Hot Jupiters (Close-in)
e) Eccentric (and/or flipped over)
f) In binary star systems

Processes forming these systems have worked in the Solar System too, but in subtler ways.
How to get the Data!

http://nexsci.caltech.edu
   -- lists of candidates and properties
http://archive.stsci.edu/kepler/
   -- download of lightcurves

A cutting-edge dataset for student research projects!