The Prevalence of Small Planets Around Small Stars from Kepler

Courtney Dressing
& David Charbonneau
Harvard-Smithsonian Center for Astrophysics

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Current & Future Missions
Targeting Planets
Around Small Stars
The M Dwarf Advantage

1 Transit Per Year
0.008% Deep
0.47% Probability

Sun G2
The M Dwarf Advantage

- Sun G2: 1 Transit Per Year, 0.008% Deep, 0.47% Probability
- Red Dwarf M4: 12 Transits Per Year, 0.13% Deep, 1.4% Probability
The M Dwarf Advantage

75% of nearby stars are M dwarfs

Sun G2

1 Transit Per Year
0.008% Deep
0.47% Probability

Red Dwarf M4

12 Transits Per Year
0.13% Deep
1.4% Probability
Computing the Planet Occurrence Rate

\[
\text{Occurrence} = \frac{\text{Actual Number of Planets}}{\text{Number of Stars Searched}}
\]

Important Corrections:

- We are not sensitive to all planets.
- Some ``planets'' might be false positives.
Revised Stellar Parameters for Kepler M Dwarfs

Dressing & Charbonneau 2013

Fit KIC photometry (Brown+ 2011) to Dartmouth stellar models (Dotter+ 2008, Feiden+ 2011) using priors on [Fe/H] and galactic height (Casagrande+ 2008)
Our 2013 Planet Occurrence Estimate

Dressing & Charbonneau 2013

0.9 planets per star with $P<50$ days and $0.5 < R_p < 4 \, R_{\text{Earth}}$

0.15 (+0.13/-0.06) Earth-size planets per HZ
Improvement 1: More Data

Sizes of Planet Candidates
As of January 7, 2013

- 1,290 - Neptune-size (2 - 6 Rₚ)
- 816 - Super Earth-size (1.25 - 2 Rₚ)
- 351 - Earth-size (< 1.25 Rₚ)
- 202 - Jupiter-size (6 - 15 Rₚ)
- 81 - Larger (15 Rₚ)

Comparison of January 2013 and February 2012 KOI lists

Image Credit: NASA
Improvement 2: **Refined Small Star Sample**

Data from Kepler Stellar Properties Table at the NASA Exoplanet Archive (Huber et al. 2014)
Improvement 3:

MEASURED PIPELINE COMPLETENESS
Our Planet Detection Pipeline

Detrend & clean Kepler light curves

Generate Box-fitting Least Squares power spectrum for each star
(Scott Fleming’s Fortran implementation of Kovacs et al. 2002)

Identify highest peaks & fit simple transit models

Excise data near accepted transits

Repeat until no new signals are detected
Pipeline Performance Versus Insolation

Detected: 241787
Not Detected: 63881
2610 Stars
305668 Simulations
Smoothed Search Completeness

![Graph showing the relationship between planet radius and insolation](image-url)
Search Completeness Versus Period

![Graph showing the relationship between planet radius and period, with sensitivity indicated by color gradient.](image)
We Recover Most KOIs

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The diagram shows a scatter plot of planet radius ($R_{\text{Earth}}$) versus period (days). The data points are color-coded as follows:

- **Candidate (82)**
- **Confirmed (75)**
- **Fractional (11)**
- **New (2)**
- **Undetected KOIs (12)**

The x-axis represents the period in days, ranging from 1 to 100, while the y-axis represents the planet radius, ranging from 0.5 to 4.0.
Possible New Mars-sized Planet Orbiting a Star without Known Planets

$P = 11.9$ Days

rp/rstar: 0.010  
ad/rstar: 26.030  
inc: 88.947  
Rp: 0.562  
Rs: 0.506  
Delta Chi Sq: 135.301  
Dur (Hr): 3.568  
Dur / Max Dur: 1.334  
Odd/Even: 0.653  
Dep Sig: 6.249  
Rat 2/1: 0.339  
Phase 2: 0.487
Possible New Earth-sized Planet in a Multi-Planet System

- P = 21.9 Days
- rp/rstar: 0.022
- a/rstar: 108.006
- inc: 90.000
- Rp: 0.962
- Rs: 0.400
- Delta Chi Sq: 81.862
-Dur (Hr): 2.067
- Dur / Max Dur: 0.745
- Odd/Even: 1.019
- Dep Sig: 6.924
- Rat 2/1: 0.278
- Phase 2: 0.421

Details:
- Phase = 0.5
- Depth: -6.74•10⁻⁴
- 3.25•10⁻⁴
- 1.32•10⁻³
Improvement 4: **Inspected Follow-up Observations** of Planet Candidates

Keck NIRC2-AO
K band
Ciardi

HST WFC3
F555W
Gilliland

Revised System Properties in Star et al. (2014)
## Improvement 5: False Positive Correction

<table>
<thead>
<tr>
<th>Class</th>
<th>Radius ($R_{\text{Earth}}$)</th>
<th>False Positive Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earths</td>
<td>0.8-1.25</td>
<td>$\textbf{12.3%} \pm 3.0%$</td>
</tr>
<tr>
<td>Super-Earths</td>
<td>1.25-2</td>
<td>$\textbf{8.8%} \pm 1.9%$</td>
</tr>
<tr>
<td>Small Neptunes</td>
<td>2-4</td>
<td>$\textbf{6.7%} \pm 1.1%$</td>
</tr>
<tr>
<td>Large Neptunes</td>
<td>4-6</td>
<td>$\textbf{15.9%} \pm 3.5%$</td>
</tr>
<tr>
<td>Giants</td>
<td>6-22</td>
<td>$\textbf{17.7%} \pm 2.9%$</td>
</tr>
</tbody>
</table>

Rates from Fressin et al. (2013)
Smoothed Population of Planet Candidates

- Planet Radius (R_{Earth})
- Period (Days)
Improvement 6: **More Sophisticated HZ Boundaries**

- Moist & Maximum greenhouse limits from Kopparapu et al. 2013

Desert worlds (Zsom et al. 2013)

Clouds (Yang et al. 2013)
Interim Summary: List of Changes

1) Used all four years of Kepler data
2) Refined stellar sample
3) Measured pipeline completeness
4) Inspected follow-up observations
5) Applied a false positive correction
6) Used more sophisticated habitable zone boundaries
Resulting Occurrence Rate

Detection Fraction < 15%
### Estimated Planet Occurrence Rate (\%) 

<table>
<thead>
<tr>
<th>Period (Days)</th>
<th>0.5</th>
<th>0.9</th>
<th>1.7</th>
<th>3.0</th>
<th>5.0</th>
<th>10.0</th>
<th>18.2</th>
<th>33.1</th>
<th>60.3</th>
<th>109.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000 (99%)</td>
<td>0.000 (100%)</td>
<td>0.000 (99%)</td>
<td>0.003 (98%)</td>
<td>0.163 (96%)</td>
<td>0.044 (98%)</td>
<td>0.553 (99%)</td>
<td>1.918 (97%)</td>
<td>0.120 (97%)</td>
<td>0.000 (85%)</td>
<td></td>
</tr>
<tr>
<td>0.003 (99%)</td>
<td>0.074 (99%)</td>
<td>1.027 (99%)</td>
<td>1.744 (98%)</td>
<td>1.5 (97%)</td>
<td>4.4 (96%)</td>
<td>16 (93%)</td>
<td>18.151 (88%)</td>
<td>9.457 (78%)</td>
<td>0.382 (47%)</td>
<td></td>
</tr>
<tr>
<td>0.459 (81%)</td>
<td>1.556 (71%)</td>
<td>5.402 (55%)</td>
<td>3.905 (55%)</td>
<td>10.426 (49%)</td>
<td>11.758 (46%)</td>
<td>8.124 (35%)</td>
<td>7.395 (18%)</td>
<td>17.330 (8%)</td>
<td>37.278 (3%)</td>
<td></td>
</tr>
<tr>
<td>0.361 (97%)</td>
<td>1.403 (96%)</td>
<td>3.450 (95%)</td>
<td>4.616 (93%)</td>
<td>9.456 (90%)</td>
<td>15.917 (86%)</td>
<td>17.266 (80%)</td>
<td>4.344 (63%)</td>
<td>17.830 (43%)</td>
<td>37.278 (19%)</td>
<td></td>
</tr>
<tr>
<td>0.000 (99%)</td>
<td>0.000 (99%)</td>
<td>0.000 (99%)</td>
<td>0.117 (98%)</td>
<td>0.338 (98%)</td>
<td>1.255 (96%)</td>
<td>0.605 (98%)</td>
<td>0.174 (99%)</td>
<td>4.029 (97%)</td>
<td>0.312 (89%)</td>
<td></td>
</tr>
</tbody>
</table>

**0.5 Earths per star with \( P < 50 \) days**
See P3.16 by Mulders for connection to planet formation.
Planet Occurrence (%) versus Flux

HZ from Kopparapu et al. 2013
### Alternative HZ Choices

#### Table 7

**HZ Occurrence Rates**

<table>
<thead>
<tr>
<th>$F_p/F_\oplus$</th>
<th>Outer HZ:</th>
<th>Inner HZ:</th>
<th>Mars</th>
<th>Venus</th>
<th>Petigura</th>
<th>Petigura</th>
<th>Max GH</th>
<th>Cloudy Moist GH</th>
<th>Max GH</th>
<th>Zsom (a=0.2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25 – 0.88</td>
<td>Max GH</td>
<td>Moist GH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8 – 1.0 $R_\oplus$</td>
<td>0.160±0.295_{-0.088} (25%)</td>
<td>0.239±0.248_{-0.092} (28%)</td>
<td>0.273±0.170_{-0.087} (37%)</td>
<td>0.227±0.211_{-0.085} (30%)</td>
<td>0.260±0.181_{-0.089} (34%)</td>
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<td></td>
</tr>
<tr>
<td>1.0 – 1.5 $R_\oplus$</td>
<td>0.186±0.214_{-0.080} (51%)</td>
<td>0.246±0.182_{-0.091} (55%)</td>
<td>0.394±0.112_{-0.074} (64%)</td>
<td>0.246±0.162_{-0.088} (58%)</td>
<td>0.324±0.127_{-0.080} (61%)</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1.5 – 2.0 $R_\oplus$</td>
<td>0.083±0.075_{-0.036} (77%)</td>
<td>0.172±0.083_{-0.053} (81%)</td>
<td>0.318±0.089_{-0.059} (86%)</td>
<td>0.206±0.085_{-0.056} (82%)</td>
<td>0.274±0.083_{-0.059} (84%)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>2.0 – 2.5 $R_\oplus$</td>
<td>0.011±0.034_{-0.008} (91%)</td>
<td>0.025±0.040_{-0.014} (91%)</td>
<td>0.083±0.048_{-0.029} (93%)</td>
<td>0.034±0.042_{-0.016} (92%)</td>
<td>0.067±0.047_{-0.026} (93%)</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5 – 4.0 $R_\oplus$</td>
<td>0.048±0.055_{-0.025} (95%)</td>
<td>0.074±0.062_{-0.033} (95%)</td>
<td>0.089±0.062_{-0.034} (96%)</td>
<td>0.079±0.061_{-0.033} (96%)</td>
<td>0.085±0.061_{-0.033} (96%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0 – 2.0 $R_\oplus$</td>
<td>0.269±0.164_{-0.087} (64%)</td>
<td>0.418±0.141_{-0.086} (68%)</td>
<td>0.712±0.003_{-0.062} (75%)</td>
<td>0.452±0.126_{-0.083} (70%)</td>
<td>0.598±0.108_{-0.073} (73%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0 – 4.0 $R_\oplus$</td>
<td>0.060±0.060_{-0.027} (94%)</td>
<td>0.099±0.067_{-0.038} (94%)</td>
<td>0.172±0.067_{-0.047} (96%)</td>
<td>0.114±0.066_{-0.039} (95%)</td>
<td>0.152±0.069_{-0.044} (96%)</td>
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</tr>
</tbody>
</table>

1.0 – 1.5 $R_{\text{Earth}}$ in Mars – Venus HZ: 0.25
1.0 – 2.0 $R_{\text{Earth}}$ in Petigura et al. (2013) HZ: 0.71
> 1 Planet Per Star for Pierrehumbert & Gaidos HZ

Nominal insolation boundaries from Kopparapu et al. 2014
Summary & Conclusions

- We refined our estimate of M dwarf planet occurrence by:
  - Using all four years of Kepler data
  - Refining stellar sample
  - Explicitly measuring pipeline completeness
  - Inspecting follow-up observations & accounting for dilution
  - Applying a false positive correction
  - Incorporating updated habitable zone boundaries

<table>
<thead>
<tr>
<th>Radius ($R_{\text{Earth}}$)</th>
<th>Period (Days)</th>
<th>Estimated Number per Star</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – 1.5</td>
<td>0.5 – 50</td>
<td>0.56 ($+0.06/-0.05$)</td>
</tr>
<tr>
<td>1.5 – 2</td>
<td>0.5 – 50</td>
<td>0.53 ($+0.07/-0.06$)</td>
</tr>
<tr>
<td>1 – 1.5</td>
<td>Narrow HZ</td>
<td>0.2 ($+0.2/-0.1$)</td>
</tr>
<tr>
<td>1-2</td>
<td>Venus – Mars HZ</td>
<td>0.4 $\pm$ 0.1</td>
</tr>
</tbody>
</table>
ADDITIONAL SLIDES
Pipeline Sensitivity

Detected: 241787
Not Detected: 63881

Only 25% of injections shown

Radius ($R_{\text{Earth}}$) vs. Period (Days)
Smaller Planets Are More Common
Potentially Habitable Worlds are Common

HZ from Kopparapu et al. 2014