Mapping Exoplanet Discoveries to Exoplanet Populations

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Detections

Surveys have produced a statistically significant sample of discoveries orbiting within 1AU down to super-earth sizes.
Exoplanet Discoveries as of Jan 2015

- **Transit (non-Kepler)**
- **Doppler**
- **Transit (Kepler)**

**Orbital Period [days]**

**Planet Radius [R_\text{e}]**

- Earth
- Neptune
- Jupiter

**Transit (non-Kepler)**

**Transit (Kepler)**

Mullally et al. 2015
Occurrence Rate Products

Using discovery catalogs to derive intrinsic populations requires careful bias corrections.
Transforming and Observed Population into an Intrinsic Population...

... requires careful bias corrections.
By design, detection efficiency is expected to be a function of MES (SNR) alone. Quantified via Monte-Carlo transit injection and recovery tests.

Christiansen et al., submitted
Photometric precision for 14 different durations are available in the Q1-Q16 star properties table at the NASA Exoplanet Archive.
Probability of Seeing 3 Transits

Duty cycle information is now available in the Q1-Q16 star properties table at the NASA Exoplanet Archive.
Geometric Alignment Probability

- **Orbital Period [days]**
- **Planet Radius [R_e]**

![Graph showing geometric alignment probability with orbital period and planet radius on axes.](image-url)
Total Detection Efficiency: Kepler-22

KeplerPORTs:

Python code hosted on github to calculate detection efficiency contours using products in the public archive at NExScI:

https://github.com/christopherburke/KeplerPORTs
Exoplanet Populations

Doppler, transit, and microlensing surveys have reported on exoplanet occurrence rates.
Both Doppler and Transit surveys report higher frequency of small planets. “Planets smaller than 2.8 R\textsubscript{e} or less massive than 30 M\textsubscript{E} are found within 0.25 AU of 30-50% of Sun-like stars.”

Mean number of planets per star for P < 50 days (a < 0.25 AU)

Image credit: Howard 2013 Science 340 572
Both Doppler and Transit surveys report higher frequency of small planets. Kepler SOC 9.1 (Q1-Q16): $P < 50$ days, $1 < R_p < 2.8$, $NPPS = 0.47 \pm 0.02$.
Sizes not seen in our Solar System

Kepler SOC 9.1 (Q1-Q16):
P < 300 days
1 < R_p < 2.8
NPPS = 0.93 +/- 0.03
Small planets are more abundant around small stars

Muoders et al. 2014
Small planets are more abundant around small stars

<table>
<thead>
<tr>
<th>SpType</th>
<th>1 – 20 Re</th>
<th>1 – 2.5 Re</th>
<th>3 – 4.5 Re</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>1.63 +/- 0.18</td>
<td>1.42 +/- 0.16</td>
<td>No Detections</td>
</tr>
<tr>
<td>K</td>
<td>1.47 +/- 0.06</td>
<td>1.07 +/- 0.05</td>
<td>0.16 +/- 0.02</td>
</tr>
<tr>
<td>G</td>
<td>1.10 +/- 0.03</td>
<td>0.68 +/- 0.02</td>
<td>0.17 +/- 0.01</td>
</tr>
</tbody>
</table>

For periods ranging from 1 to 300 days
Dawson & Murray-Clay 2013:

all giants: 0.0038 +/- 0.0008
FeH > 0: 0.0108 +/- 0.33
FeH < 0: 0.0025 +/- 0.0008
Q1-Q16 (SOC 9.1 codebase) data products are available at the NExSci Archive. Their use is illustrated in Burke et al. 2015: http://arxiv.org/abs/1506.04175
Analyze Small Planets with Intermediate Periods

50 < Period < 300 [day]
0.75 < Rp < 2.5 [Rearth]

Catalog: Mullally et al. (2015)
4200 – 6100 K ~ GK V
5 Parameter Model

Broken power-law in planet radius
- \( R_{brk} \)
- \( \alpha_1 \)
- \( \alpha_2 \)

power-law in orbital period
- \( \beta \)

Normalization
- \( F_o \)

Bayesian Parameter Estimation
- MCMC methods; Poisson Likelihood
Intrinsic Planet Distribution & Detection Bias Model Fitting

Model Fit
Posterior regions
1-sig & 3-sig

Observed Counts
Remove The Detection Bias Component

Intrinsic Planet Distribution

Increasing Planet Occurrence Toward Terrestrial Planets

Average number of planets per star integrated over this phase space: 0.77 +/- 0.12
Systematic Errors > Statistical Errors

![Graph showing planet occurrence probability density for various conditions.](image)

- Optimistic Efficiency
- Pessimistic Efficiency
- Eccentric
- Original KIC
- DV Rp
- Low Reliability
- High Reliability
- First Planet Only
- Baseline

Conditions:

\[ 1.0 < R_p < 2.0 \ R_\oplus \ ; \ 50 < P_{\text{orb}} < 200 \ \text{day} \]
Kepler’s ExoPop Hack

Dates: October 13, 14, 15
Duration: Three days
Participation: < 25, including project personnel
Core participants:
  Andrew Howard, UH
  Courtney Dressing, Cal Tech
  David Hogg, NYU
  Daniel Foreman-Mackey, UW
  Darin Ragozzine
  Gijs Mulders, UA
Location:
  ARC, Building 232
Small HZ Planets

The challenge is to improve sensitivity, quantify false alarm rate, and compute realistic uncertainties.
Table 2. Occurrence rates of “Earth-like planets”

<table>
<thead>
<tr>
<th>Type of star</th>
<th>Type of planet</th>
<th>Approx. HZ boundaries* [S/S(\oplus)]</th>
<th>Occurrence rate [%]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>1-10 (M_\oplus)</td>
<td>0.75-2.0</td>
<td>41(^{+54}_{-13})</td>
<td>1</td>
</tr>
<tr>
<td>FGK</td>
<td>0.8-2.0 (R_\oplus)</td>
<td>0.3-1.8</td>
<td>2.8(^{+1.9}_{-0.9})</td>
<td>2</td>
</tr>
<tr>
<td>FGK</td>
<td>0.5-2.0 (R_\oplus)</td>
<td>0.8-1.8</td>
<td>34 (\pm 14)</td>
<td>3</td>
</tr>
<tr>
<td>M</td>
<td>0.5-1.4 (R_\oplus)</td>
<td>0.46-1.0</td>
<td>15(^{+13}_{-6})</td>
<td>4</td>
</tr>
<tr>
<td>M</td>
<td>0.5-1.4 (R_\oplus)</td>
<td>0.22-0.80</td>
<td>48(^{+12}_{-24})</td>
<td>5</td>
</tr>
<tr>
<td>GK</td>
<td>1-2 (R_\oplus)</td>
<td>0.25-4.0</td>
<td>11 (\pm 4)</td>
<td>6</td>
</tr>
<tr>
<td>FGK</td>
<td>1-2 (R_\oplus)</td>
<td>0.25-4.0(^{+})</td>
<td>(\sim 0.01)(^{+})</td>
<td>7</td>
</tr>
<tr>
<td>FGK</td>
<td>1-4 (R_\oplus)</td>
<td>0.35-1.0</td>
<td>6.4(^{+3.4}_{-1.1})</td>
<td>8</td>
</tr>
<tr>
<td>G</td>
<td>0.6-1.7 (R_\oplus)</td>
<td>0.51-1.95</td>
<td>1.7(^{+1.8}_{-0.9})</td>
<td>9</td>
</tr>
</tbody>
</table>

Note. — References: (1) Bonfils et al. (2013), (2) Catanzarite & Shao (2011), (3) Traub (2012), (4) Dressing & Charbonneau (2013), (5) Kopparapu (2013), (6) Petigura et al. (2013), (7) Schlaufman (2014), (8) Silburt et al. (2014), (9) Foreman-Mackey et al. (2014). In column 3, \(S\) refers to the incident flux of starlight on the planet, and \(S_\oplus\) to the Earth’s insolation. All these works are based on \emph{Kepler} data except (1) which is based on the HARPS Doppler survey, and (5) which is based on the 

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“... the uncertainty is limited for the foreseeable future by our ignorance of the appropriate limits of integration.” Winn & Fabrycky 2014 ARAA
ExoPAG SAG-13

SAG-13: Exoplanet Occurrence Rates and Distributions

• Chair: Rus Belikov

• Objectives:
  – Establish standard definitions and conventions (e.g. definition of eta-earth, size range for terrestrial planets)
  – Resolve differences between various methodologies
  – Establish baseline measurements for meaningful comparison of planet yield between mission design studies

• Face-to-face meeting to coincide with Kepler Hack Week in October, either day before or day after
Small (< 2 $R_e$) Planets in the HZ: 1 yr

Surface Temperature of Host Star vs. Stellar Flux Received by Planet, $F_p/F_e$

- Empirical HZ
- Narrow HZ
- In HZ, symbol scaled to size of Earth

HZ def’n: Kopparapu et al 2013, updated by Leconte et al 2014
Small ($< 2 \, R_e$) Planets in the HZ: 2 yr

- Energy Received by Planet
- Surface Temperature of Host Star

- Empirical HZ
- Narrow HZ
- In HZ, symbol scaled to size of Earth

HZ def’n: Kopparapu et al 2013, updated by Leconte et al 2014
Small (< 2 R_e) Planets in the HZ: 3 yr

Stellar Flux Received by Planet, $F_p/F_e$

Surface Temperature of Host Star

Empirical HZ  Narrow HZ  In HZ, symbol scaled to size of Earth

HZ def’n: Kopparapu et al 2013, updated by Leconte et al 2014
Energy Received by Planet

Surface Temperature of Star

<table>
<thead>
<tr>
<th>VE</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>3500</td>
<td>4500</td>
</tr>
<tr>
<td>5500</td>
<td>6500</td>
</tr>
</tbody>
</table>

Small (< 2 \(R_e\)) Planets in the HZ: 4 yr

- Empirical HZ
- Narrow HZ
- In HZ, symbol scaled to size of Earth

Stellar Flux Received by Planet, \(F_p/F_e\)

Surface Temperature of Host Star

HZ def’n: Kopparapu et al 2013, updated by Leconte et al 2014
Quantifying the False Alarm Rate

Credit: Shawn Seader, Jon Jenkins
Small (< 2 R\textsubscript{e}) Planets in the HZ: 4 yr

HZ def’n: Kopparapu et al 2013, updated by Leconte et al 2014
Small (<2 R\textsubscript{e}) Planets in the HZ: 4 yr

For size range: 1 – 1.6 R\textsubscript{e}

Weighted mean: 0.15 (0.05)

Uncertainties include only statistical errors.
Mass-Radius Diagram

We can make statistical inferences about composition using posterior distributions on planet mass from RV campaigns and transit timing analyses.
Mass and Radius of Kepler-138 Planets

- Kepler-138d
- Kepler-138c
- Kepler-138b
- Earth
- Venus
- Mars
- Mercury

GASEOUS
MIXED
ROCKY

Size Relative to Earth (Radius)
Mass Relative to Earth

Jontoff-Hunter et al. 2015

Kepler-138 planets
Solar system planets
Kepler planets

Legend:
Closing Comments:

- Efforts in the Kepler closeout (9/15 – 9/17) are focused on delivering legacy data products that enable population studies beyond mission closeout. SOC 9.1 products and tools are available.

- At present, systematic errors in Kepler occurrence rates are larger than the statistical errors. Reducing them to <10% is also the focus of the closeout effort.

- Kepler will yield eta-Earth estimates for G, K, and M stars but suffers from small sample sizes for earth-sun analogs.

- Filling in the mass-radius diagram is critical for understanding which planets are most likely to harbor life. Both TTVs and RVs are making important contributions.