Toward Reliable Planet Occurrence Rates

with

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Reguirements for Reliable n_{earth}

Planet Occurrence Rates: Basic Framework

Observed Catalog Detection Intrinsic
Distribution Reliability Probability Distribution
$$O(R_p, P) * R(R_p, P) = P_{tot}(R_p, P) * I(R_p, P)$$
$$P_{tot}(R_p, P) = \sum_{i=1}^{Nstars} P_{i,1}(R_p, P) * P_{i,2}(R_p, P) * P_{i,3}(R_p, P) \dots$$

Occurrence rates are expressed as a distribution over planet size, period, insolation flux, and/or star type with corrections for both catalog reliability and catalog incompleteness.



Requirements for a reliable eta-Earth determination



- 1)Sensitivity to earth-size planets in the HZ of G (K & M) stars.
- 2)Uniform detection catalog with posterior distributions on the planet properties.
- 3) Knowledge of Kepler's detection efficiency (completeness)
- 4)Knowledge of the catalog reliability
- 5) Well-documented and accessible data products for postmission analysis by the community.

Sensitivity to Small HZ Planets



Catalog Status



The Kepler prime mission has a three-year close-out period (10/1/2014 to 9/30/2014) to finalize pipeline development, the exoplanet catalog, and occurrence rate products.

Data	Author	KOI #	Candidates	Status	Date		
Q0 – Q1	Borucki 1	956	312	published	Feb, 2011		
Q1 – Q5	Borucki 2	1610	1235	published	July, 2011		
Q1 – Q6	Batalha	2668	2338	published	Feb, 2012		
Q1 – Q8	Burke	3149 2738 published		Dec, 2013			
Q1 – Q12	Rowe	4914	4 3579 completing		Nov, 2014		
Q1 – Q16	Mullally	6251	4168 completing		Nov, 2014		
Q1 – Q17		S	2015				
Q1 – Q17		SOC 9.3	2016				
Q1 – Q17		S	2017				

* See poster by Jeff Smith: significant improvements to SNR reported



Sensitivity to small HZ planets



697 non-Kepler planets
90% <u>larger</u> than Neptune
583 unique stars
16% are multi-planet systems



3850 Kepler planet candidates
84% smaller than Neptune
2939 unique stars
22% are multi-planet systems

Kepter Automating the Catalog Generation



95.9%, 93.4%, 86.6% agreement with humans at SNR > 20, 10, 7.1 Credit: Jeff Coughlin









Bootstrap Statistic





Credit: Shawn Seader, Fergal Mullally

Well characterized planet properties

Well-understood star & planet properties

Radius versus effective temperature of the ~190,000 stars observed by Kepler during the prime mission.

Upper panel: properties used for the 12 quarter pipeline run.

Lower panel: properties used for the 16 quarter pipeline run.

Figure taken from Huber et al. 2014, ApJS, 211, 2.



Catalog Reliability: Star and Planet Properties

Star Properties Working Group charter includes:

 Deliver catalog of reliable star properties (T_{eff}, logg, R_{*}, M_{*}) for the entire Kepler target sample. (chair: D. Huber, **PSP**)

Resources:

- KIC photometry (Brown et al. 2011)
- Published systematic errors (e.g. Pinsonneault et al. 2012)
- Properties Derived from Kepler Photometry (e.g. Bastien et al. 2013)
- Asteroseismology (**KASC**; e.g. Chaplin '11, Silva Aguirre '11, Bedding '10)
- Spectroscopic Surveys: **FOP**, APOGEE, LAMOST, VIRUS (Endl **PSP**)
- Photometric Surveys: UBV, Panstarrs z, Strömgren, Kepler-INT (Ugri)
- Imaging surveys: **FOP** (Keck, Palomar, Gemini), RoboAO

Deliveries (to coincide with pipeline runs):

- Intermediate catalogs that provide corrections to KIC, superceded by properties in the published literature where available
- Final catalog based on analysis of all the available photometry and calibrated against a control sample.



Understanding Systematics



Credit: Jason Rowe



Understanding Systematics





Credit: Jason Rowe







Credit: Jason Rowe

Quantitative Knowledge of the Detection Efficiency

Transit Injection Tests



Front end of the pipeline does a very good job preserving transit signals.

Only 0.9% of targets experience significant suppression. 98% fidelity preserving singletransit SNR (3% scatter in SNR)



MS = 0.9973 (+/- 0.0011) x BS - 0.0151 (+/- 0.0049) Christiansen et al 2013, ApJS, 207, 35 (PSP)

Transit Injection Tests



Monte Carlo transit injection in10,080 flux timeseries.

Planets with sizes ranging from 0.5 to 3.0 Re

Periods ranging from 50 to 150 days

Pink: gaussian error function

Seader et al. 2013, ApJS, 206, 25



Dis-

posi-

tion

Knowledge of detection completeness

d ci P N	let:<1 forr:124 Pdet=0.00808 IPPS:<0.0044	det:<1 corr:133 Pdet=0.00750 NPPS:<0.0048	det:<1 corr:144 Pdet=0.00696 NPPS:<0.0052	det:<1 corr:155 Pdet=0.00645 NPPS:<0.0056	det:<1 corr:167 Pdet=0.00597 NPPS:<0.0060	det:<1 corr:181 Pdet=0.00552 NPPS:<0.0065	det:<1 corr:196 Pdet=0.00509 NPPS:<0.0070	det:<1 corr:214 Pdet=0.00468 NPPS:<0.0077	det:<1 corr:234 Pdet=0.00427 NPPS:<0.0084	det:<1 corr:259 Pdet=0.00386 NPPS:<0.0093	det:<1 corr:290 Pdet=0.00345 NPPS:<0.0104	det:<1 corr:330 Pdet=0.00303 NPPS:<0.0118	det:<1 corr:385 Pdet=0.00260 NPPS:<0.0138	det:<1 corr:463 Pdet=0.00216 NPPS:<0.0166	det:<1 corr:577 Pdet=0.00173 NPPS:<0.0207	det:<1 corr:0 Pdet=0.00000 NPPS:<0.0000
d ci P N	let:<1 forr:124 Pdet=0.00808 IPPS:<0.0044	det:<1 corr:133 Pdet=0.00750 NPPS:<0.0048	det:<1 corr:144 Pdet=0.00696 NPPS:<0.0052	det:<1 corr:155 Pdet=0.00645 NPPS:<0.0056	det:<1 corr:167 Pdet=0.00597 NPPS:<0.0060	det:<1 corr:181 Pdet=0.00552 NPPS:<0.0065	det:<1 corr:196 Pdet=0.00509 NPPS:<0.0070	det:1 corr:210 Pdet=0.00467 NPPS:0.0075 sNPPS:0.0075	det:<1 corr:234 Pdet=0.00427 NPPS:<0.0084	det:1 corr:271 Pdet=0.00386 NPPS:0.0097	det:<1 corr:290 Pdet=0.00345 NPPS:<0.0104	det:<1 corr:330 Pdet=0.00303 NPPS:<0.0118	det:<1 corr:385 Pdet=0.00260 NPPS:<0.0138	det:<1 corr:463 Pdet=0.00216 NPPS:<0.0166	det:<1 corr:577 Pdet=0.00173 NPPS:<0.0207	det:<1 corr:0 Pdet=0.00000 NPPS:<0.0000
4 ci P N	let:<1 corr:124 Pdet=0.00807 IPPS:<0.0044	det:<1 corr:133 Pdet=0.00749 NPPS:<0.0048	det:<1 corr:144 Pdet=0.00695 NPPS:<0.0052	det:<1 corr:155 Pdet=0.00644 NPPS:<0.0056	det:2 corr:331 Pdet=0.00597 NPPS:0.0119 sNPPS:0.0084	det:<1 corr:181 Pdet=0.00552 NPPS:<0.0065	det:1 corr:190 Pdet=0.00509 NPPS:0.0068	det:<1 corr:214 Pdet=0.00467 NPPS:<0.0077	det:<1 corr:234 Pdet=0.00427 NPPS:<0.0084	det:<1 corr:259 Pdet=0.00386 NPPS:<0.0093	det:<1 corr:290 Pdet=0.00345 NPPS:<0.0104	det:1 corr:325 Pdet=0.00303 NPPS:0.0117 sNPPS:0.0117	det:<1 corr:385 Pdet=0.00259 NPPS:<0.0138	det:<1 corr:463 Pdet=0.00216 NPPS:<0.0166	det:<1 corr:577 Pdet=0.00173 NPPS:<0.0207	det:<1 corr:0 Pdet=0.00000 NPPS:<0.0000
6 ci P N	let:<1 corr:125 Pdet=0.00801 NPPS:<0.0045	det:<1 corr:134 Pdet=0.00744 NPPS:<0.0048	det:<1 corr:145 Pdet=0.00690 NPPS:<0.0052	det:<1 corr:156 Pdet=0.00640 NPPS:<0.0056	det:<1 corr:169 Pdet=0.00593 NPPS:<0.0060	det:<1 corr:182 Pdet=0.00548 NPPS:<0.0065	det:<1 corr:198 Pdet=0.00506 NPPS:<0.0071	det:<1 corr:215 Pdet=0.00465 NPPS:<0.0077	det:1 corr:244 Pdet=0.00424 NPPS:0.0088	det:1 corr:260 Pdet=0.00384 NPPS:0.0093	det:<1 corr:291 Pdet=0.00343 NPPS:<0.0105	det:<1 corr:332 Pdet=0.00301 NPPS:<0.0119	det:<1 corr:387 Pdet=0.00258 NPPS:<0.0139	det:<1 corr:466 Pdet=0.00215 NPPS:<0.0167	det:<1 corr:580 Pdet=0.00172 NPPS:<0.0208	det:<1 corr:0 Pdet=0.00000 NPPS:<0.0000
4 c P N	let:1 orr:137 Pdet=0.00774 IPPS:0.0049	det:<1 corr:139 Pdet=0.00717 NPPS:<0.0050	det:1 corr:160 Pdet=0.00664 NPPS:0.0057 sNPPS:0.0057	det:3 corr:476 Pdet=0.00614 NPPS:0.0171 sNPPS:0.0099	det:1 corr:175 Pdet=0.00567 NPPS:0.0063 sNPPS:0.0063	det:<1 corr:192 Pdet=0.00522 NPPS:<0.0069	det:<1 corr:209 Pdet=0.00479 NPPS:<0.0075	det:<1 corr:228 Pdet=0.00438 NPPS:<0.0082	det:1 corr:297 Pdet=0.00397 NPPS:0.0107	det:1 corr:283 Pdet=0.00357 NPPS:0.0101	det:<1 corr:316 Pdet=0.00317 NPPS:<0.0113	det:1 corr:448 Pdet=0.00276 NPPS:0.0161 sNPPS:0.0161	det:<1 corr:424 Pdet=0.00236 NPPS:<0.0152	det:2 corr:1285 Pdet=0.00196 NPPS:0.0461 sNPPS:0.0326	det:1 corr:628 Pdet=0.00157 NPPS:0.0225 sNPPS:0.0225	det:<1 corr:0 Pdet=0.00000 NPPS:<0.0000
9 d c P N	let:<1 .orr:178 Pdet=0.00563 IPPS:<0.0064	det:<1 corr:197 Pdet=0.00506 NPPS:<0.0071	det:<1 corr:220 Pdet=0.00454 NPPS:<0.0079	det:<1 corr:246 Pdet=0.00407 NPPS:<0.0088	det:<1 corr:275 Pdet=0.00363 NPPS:<0.0099	det:<1 corr:309 Pdet=0.00323 NPPS:<0.0111	det:<1 corr:349 Pdet=0.00287 NPPS:<0.0125	det:1 corr:316 Pdet=0.00253 NPPS:0.0113 sNPPS:0.0113	det:<1 corr:450 Pdet=0.00222 NPPS:<0.0161	det:2 corr:801 Pdet=0.00194 NPPS:0.0287 sNPPS:0.0203	det:1 corr:472 Pdet=0.00167 NPPS:0.0169 sNPPS:0.0169	det:<1 corr:700 Pdet=0.00143 NPPS:<0.0251	det:<1 corr:833 Pdet=0.00120 NPPS:<0.0299	det:<1 corr:1010 Pdet=0.00099 NPPS:<0.0362	det:<1 corr:1251 Pdet=0.00080 NPPS:<0.0449	det:<1 corr:0 Pdet=0.00000 NPPS:<0.0000
3 d c P N	let:<1 orr:528 Pdet=0.00189 JPPS:<0.0189	det:1 corr:674 Pdet=0.00164 NPPS:0.0242 sNPPS:0.0242	det:1 corr:809 Pdet=0.00142 NPPS:0.0290 sNPPS:0.0290	det:<1 corr:814 Pdet=0.00123 NPPS:<0.0292	det:<1 corr:944 Pdet=0.00106 NPPS:<0.0338	det:<1 corr:1096 Pdet=0.00091 NPPS:<0.0393	det:<1 corr:1277 Pdet=0.00078 NPPS:<0.0458	det:<1 corr:1491 Pdet=0.00067 NPPS:<0.0535	det:<1 corr:1748 Pdet=0.00057 NPPS:<0.0627	det:<1 corr:2059 Pdet=0.00049 NPPS:<0.0738	det:<1 corr:2439 Pdet=0.00041 NPPS:<0.0875	det:1 corr:1762 Pdet=0.00034 NPPS:0.0632 sNPPS:0.0632	det:<1 corr:3512 Pdet=0.00028 NPPS:<0.1260	det:1 corr:2253 Pdet=0.00023 NPPS:0.0808 sNPPS:0.0808	det:<1 corr:5313 Pdet=0.00019 NPPS:<0.1905	det:<1 corr:0 Pdet=0.00000 NPPS:<0.0000
2 d c P N	let:<1 corr:2781 Pdet=0.00036 IPPS:<0.0997	det:<1 corr:3295 Pdet=0.00030 NPPS:<0.1182	det:<1 corr:3913 Pdet=0.00026 NPPS:<0.1403	det:<1 corr:4658 Pdet=0.00021 NPPS:<0.1671	det:<1 corr:5560 Pdet=0.00018 NPPS:<0.1994	det:<1 corr:6654 Pdet=0.00015 NPPS:<0.2386	det:<1 corr:7987 Pdet=0.00013 NPPS:<0.2865	det:<1 corr:9618 Pdet=0.00010 NPPS:<0.3449	det:<1 corr:11625 Pdet=0.00009 NPPS:<0.4169	det:<1 corr:14107 Pdet=0.00007 NPPS:<0.5059	det:<1 corr:17209 Pdet=0.00006 NPPS:<0.6172	det:<1 corr:21128 Pdet=0.00005 NPPS:<0.7577	det:<1 corr:26151 Pdet=0.00004 NPPS:<0.9379	det:<1 corr:32703 Pdet=0.00003 NPPS:<1.1728	det:<1 corr:41423 Pdet=0.00002 NPPS:<1.4855	det:<1 corr:0 Pdet=0.00000 NPPS:<0.0000
d c P N	let:<1 corr:25124 Pdet=0.00004 IPPS:<0.9010	det:1 corr:101332 Pdet=0.00003 NPPS:3.6341 sNPPS:3.6341	det:<1 corr:38635 Pdet=0.00003 NPPS:<1.3856	det:1 corr:23586 Pdet=0.00002 NPPS:0.8459 sNPPS:0.8459	det:<1 corr:60629 Pdet=0.00002 NPPS:<2.1743	det:<1 corr:76631 Pdet=0.00001 NPPS:<2.7482	det:<1 corr:97458 Pdet=0.00001 NPPS:<3.4951	det:<1 corr:124871 Pdet=0.00001 NPPS:<4.4782	det:<1 corr:161194 Pdet=0.00001 NPPS:<5.7809	det:<1 corr:209793 Pdet=0.00000 NPPS:<7.5238	det:<1 corr:275633 Pdet=0.00000 NPPS:<9.8850	det:<1 corr:365326 Pdet=0.00000 NPPS:<13.1016	det:<1 corr:489325 Pdet=0.00000 NPPS:<17.5486	det:<1 corr:661599 Pdet=0.00000 NPPS:<23.7268	det:<1 corr:902510 Pdet=0.00000 NPPS:<32.3666	det:<1 corr:0 Pdet=0.00000 NPPS:<0.0000
d ci P	let:1 orr:2850016 Pdet=0.00000 IPPS:102.2097	det:1 corr:2916746 Pdet=0.00000 NPPS:104.6029	det:<1 corr:1057772 Pdet=0.00000 NPPS:<37.9347	det:<1 corr:1353698 Pdet=0.00000 NPPS:<48.5475	det:<1 corr:1733332 Pdet=0.00000 NPPS:<62.1622	det:2 corr:13003770 Pdet=0.00000 NPPS:466.3524	det:2 corr:31679768 Pdet=0.00000 NPPS:1136.1271	det:<1 corr:3841336 Pdet=0.00000 1 NPPS:<137.7613	det:<1 corr:5115429 Pdet=0.00000 NPPS:<183.4539	det:1 corr:2087588 Pdet=0.00000 NPPS:74.8669	det:<1 corr:9450717 Pdet=0.00000 NPPS:<338.929	det:<1 corr:13157662 Pdet=0.00000 8 NPPS:<471.8714	det:<1 corr:18923839 Pdet=0.00000 NPPS:<678.663	det:<1 corr:28012328 Pdet=0.00000 NPPS:<1004.602	det:<1 corr:43540279 Pdet=0.00000 22NPPS:<1561.478	det:<1 corr:0 Pdet=0.00000 39NPPS:<0.0000

Sum of all detection probability contours (radius versus insolation flux) of K-type main sequence stars. Credit: Eduardo Seperuelo Duarte

Knowledge of detection completeness

5300 K < Teff < 6	6000: Nstars= 6464	6: Nplanets= 92
		0 , 1

det:<1 corr:171 Pdet=0.00584 NPPS:<0.002	det:<1 corr:187 Pdet=0.00536 6 NPPS:<0.0029	det:<1 corr:205 Pdet=0.00488 NPPS:<0.0032	det:<1 corr:227 Pdet=0.00441 NPPS:<0.0035	det:<1 corr:255 Pdet=0.00393 NPPS:<0.0039	det:<1 corr:291 Pdet=0.00343 NPPS:<0.0045	det:<1 corr:341 Pdet=0.00293 NPPS:<0.0053	det:<1 corr:413 Pdet=0.00242 NPPS:<0.0064	det:<1 corr:523 Pdet=0.00191 NPPS:<0.0081	det:<1 corr:702 Pdet=0.00142 NPPS:<0.0109	det:<1 corr:1019 Pdet=0.00098 NPPS:<0.0158	det:<1 corr:1631 Pdet=0.00061 NPPS:<0.0252	det:<1 corr:2932 Pdet=0.00034 NPPS:<0.0454	det:<1 corr:6124 Pdet=0.00016 NPPS:<0.0947	det:<1 corr:16040 Pdet=0.00006 NPPS:<0.2481	det:<1 corr:0 Pdet=0.00000 NPPS:<0.0000
det:<1 corr:171 Pdet=0.00584 NPPS:<0.002	det:<1 corr:187 Pdet=0.00536 NPPS:<0.0029	det:1 corr:210 Pdet=0.00488 NPPS:0.0032	det:<1 corr:227 Pdet=0.00441 NPPS:<0.0035	det:<1 corr:255 Pdet=0.00392 NPPS:<0.0039	det:<1 corr:291 Pdet=0.00343 NPPS:<0.0045	det:<1 corr:341 Pdet=0.00293 NPPS:<0.0053	det:<1 corr:413 Pdet=0.00242 NPPS:<0.0064	det:<1 corr:523 Pdet=0.00191 NPPS:<0.0081	det:<1 corr:702 Pdet=0.00142 NPPS:<0.0109	det:<1 corr:1019 Pdet=0.00098 NPPS:<0.0158	det:<1 corr:1631 Pdet=0.00061 NPPS:<0.0252	det:<1 corr:2933 Pdet=0.00034 NPPS:<0.0454	det:<1 corr:6124 Pdet=0.00016 NPPS:<0.0947	det:<1 corr:16041 Pdet=0.00006 NPPS:<0.2481	det:<1 corr:0 Pdet=0.00000 NPPS:<0.0000
4 det:<1 corr:171 Pdet=0.00584 NPPS:<0.002	det:<1 corr:187 Pdet=0.00536 7 NPPS:<0.0029	sNPPS:0.0032 det:1 corr:213 Pdet=0.00488 NPPS:0.0033	det:<1 corr:227 Pdet=0.00440 NPPS:<0.0035	det:1 corr:261 Pdet=0.00392 NPPS:0.0040	det:2 corr:605 Pdet=0.00343 NPPS:0.0094	det:<1 corr:341 Pdet=0.00293 NPPS:<0.0053	det:<1 corr:413 Pdet=0.00242 NPPS:<0.0064	det:2 corr:969 Pdet=0.00191 NPPS:0.0150	det:<1 corr:703 Pdet=0.00142 NPPS:<0.0109	det:<1 corr:1020 Pdet=0.00098 NPPS:<0.0158	det:<1 corr:1631 Pdet=0.00061 NPPS:<0.0252	det:<1 corr:2934 Pdet=0.00034 NPPS:<0.0454	det:<1 corr:6126 Pdet=0.00016 NPPS:<0.0948	det:<1 corr:16043 Pdet=0.00006 NPPS:<0.2482	det:<1 corr:0 Pdet=0.00000 NPPS:<0.0000
det:<1 corr:172 Pdet=0.00582 NPPS:<0.002	det:4 corr:762 2 Pdet=0.00534 7 NPPS:0.0118 sNPPS:0.0059	det:1 corr:205 Pdet=0.00486 NPPS:0.0032 sNPPS:0.0032	det:<1 corr:228 Pdet=0.00439 NPPS:<0.0035	det:1 corr:275 Pdet=0.00391 NPPS:0.0043 sNPPS:0.0043	det:2 corr:583 Pdet=0.00342 NPPS:0.0090 sNPPS:0.0064	det:<1 corr:343 Pdet=0.00292 NPPS:<0.0053	det:1 corr:382 Pdet=0.00241 NPPS:0.0059 sNPPS:0.0059	det:<1 corr:526 Pdet=0.00190 NPPS:<0.0081	det:<1 corr:706 Pdet=0.00142 NPPS:<0.0109	det:<1 corr:1025 Pdet=0.00098 NPPS:<0.0159	det:<1 corr:1640 Pdet=0.00061 NPPS:<0.0254	det:<1 corr:2948 Pdet=0.00034 NPPS:<0.0456	det:<1 corr:6154 Pdet=0.00016 NPPS:<0.0952	det:1 corr:25809 Pdet=0.00006 NPPS:0.3992 sNPPS:0.3992	det:<1 corr:0 Pdet=0.00000 NPPS:<0.0000
det:3 corr:563 Pdet=0.00543 NPPS:0.0087 sNPPS:0.005	det:3 corr:590 Pdet=0.00493 NPPS:0.0091 0 sNPPS:0.0053	det:1 corr:224 Pdet=0.00445 NPPS:0.0035 sNPPS:0.0035	det:2 corr:522 Pdet=0.00397 NPPS:0.0081 sNPPS:0.0057	det:2 corr:725 Pdet=0.00349 NPPS:0.0112 sNPPS:0.0079	det:2 corr:813 Pdet=0.00301 NPPS:0.0126 sNPPS:0.0089	det:2 corr:863 Pdet=0.00254 NPPS:0.0133 sNPPS:0.0094	det:<1 corr:483 Pdet=0.00207 NPPS:<0.0075	det:1 corr:681 Pdet=0.00162 NPPS:0.0105 sNPPS:0.0105	det:<1 corr:836 Pdet=0.00120 NPPS:<0.0129	det:1 corr:1705 Pdet=0.00082 NPPS:0.0264 sNPPS:0.0264	det:2 corr:4196 Pdet=0.00051 NPPS:0.0649 sNPPS:0.0459	det:<1 corr:3481 Pdet=0.00029 NPPS:<0.0538	det:<1 corr:7201 Pdet=0.00014 NPPS:<0.1114	det:<1 corr:18533 Pdet=0.00005 NPPS:<0.2867	det:<1 corr:0 Pdet=0.00000 NPPS:<0.0000
det:6 corr:2851 Pdet=0.00272 NPPS:0.0441 sNPPS:0.018	det:2 corr:975 Pdet=0.00237 NPPS:0.0151 0 sNPPS:0.0107	det:5 corr:3331 Pdet=0.00204 NPPS:0.0515 sNPPS:0.0230	det:1 corr:793 Pdet=0.00175 NPPS:0.0123 sNPPS:0.0123	det:1 corr:538 Pdet=0.00148 NPPS:0.0083 sNPPS:0.0083	det:3 corr:4588 Pdet=0.00123 NPPS:0.0710 sNPPS:0.0410	det:4 corr:7056 Pdet=0.00100 NPPS:0.1092 sNPPS:0.0546	det:1 corr:1345 Pdet=0.00079 NPPS:0.0208 sNPPS:0.0208	det:3 corr:4852 Pdet=0.00060 NPPS:0.0751 sNPPS:0.0433	det:<1 corr:2277 Pdet=0.00044 NPPS:<0.0352	det:1 corr:4165 Pdet=0.00030 NPPS:0.0644 sNPPS:0.0644	det:3 corr:15012 Pdet=0.00019 NPPS:0.2322 sNPPS:0.1341	det:<1 corr:9528 Pdet=0.00010 NPPS:<0.1474	det:<1 corr:19352 Pdet=0.00005 NPPS:<0.2994	det:<1 corr:47954 Pdet=0.00002 NPPS:<0.7418	det:<1 corr:0 Pdet=0.00000 NPPS:<0.0000
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Sum of all detection probability contours (radius versus insolation flux) of G-type main sequence stars. Credit: Eduardo Seperuelo Duarte

Quantitative Knowledge of the Catalog Reliability

KOI 7.01



Catalog Reliability: False Positive Probabilities

A false positive probability is computed for each planet candidate. Contour is the average FPP as a function of radius and period.



Credit: T. Morton

Catalog Reliability: False Positive Probabilities

A false positive probability is computed for each planet candidate. Each red point is the mean for that radius bin.



80% have FPP < 5%

Credit: T. Morton

Current Status

- Borucki et al. 2011 ApJ 736 19, Characteristics of Planetary Candidates Observed by Kepler. II.
- Catanzarite & Shao 2011 ApJ 738 151, The Occurrence Rate of Earth Analog Planets Orbiting Sun-like Stars
- Youdin 2011 ApJ 742 38, The Exoplanet Census: A General Method Applied to Kepler
- Gould & Eastman 2011 arXiv:1102.1009
- <u>Traub 2012 ApJ 745 20</u>, Terrestrial, Habitable-Zone Exoplanet Frequency from Kepler
- Howard et al. 2012 ApJS 201 15, Planet Occurrence within 0.25 AU of Solar-type Stars from Kepler
- Dong & Zhu 2012 arXiv:1212.4853, Statistics of Kepler Planet Candidates Up to 0.75 AU
- Mann et a. 2012 ApJ 753 90, The May be Giants: Luminosity Class, Occurrence, and Metallicity Relations
- Gaidos & Mann 2013 ApJ 762 41, Objects in Kepler's Mirror May be Larger than they Appear
- Beaugé & Nesvorny 2013 ApJ 763 12, Emerging Trends in a Period-Radius Distribution of Close-In Planets
- Fressin et al 2013 ApJ 766 81, The False Positive Rate of Kepler and the Occurrence of Planets
- Dressing & Charbonneau 2013 ApJ 767 95, The Occurrence Rate of Small Planets around Small Stars
- Swift et al. 2013 ApJ 764 105, Characterizing the Cool KOIs. IV
- <u>Petigura et al 2013 ApJ 770 69</u>, A Plateau in the Planet Population Below Twice the Size of Earth
- <u>Gaidos 2013 ApJ 770 90</u>, Candidate Planets in the Habitable Zones of Kepler Stars
- Kopparapu 2013 ApJ 767 8, A Revised Estimate of the Occurrence Rate of Terrestrial Planets in the HZ around M-dwarfs
- Morton & Swift arXiv:1303.3013, The Radius Distribution of Small Planets Around Cool Stars
- Gaidos 2013 ApJ 771 18, An Understanding of the Shoulder of Giants: Jovian Planets...
- <u>Petigura et al 2013 PNAS 110 19273</u>, Prevalence of Earth-size planets orbiting Sun-like stars.
- <u>Mulders, Pascucci, Apai 2014 arXiv:1406.7356</u> A stellar-mass-dependent drop in planet occurrence rates and the abundance of Earth analogs from noisy, incomplete catalogs
- Kane, Kopparapu, Domagal-Goldman 2014 arXiv:1409.2886 On the frequence of Potential Venus Analogs from Kepler, Data



- Stellar Parameters
 - Q1-16 Star Catalog (Huber et al. 2014)
 - Teff < 7000 K ; Rstar < 1.15 Rsun
 - 119,600 Kepler targets
- Planet Parameters
 - Q1-16 Planet Candidate Sample (Mullally et al. in prep.)
 - 50<Porb<300 day ; Rp < 5 Rearth
 - 397 Planet Candidates
- Pipeline Completeness
 - Analytic Star-by-star Detection Model
 - Calibrated With Transit Injection & Recovery
- Methodology
 - Parametric (broken power-law) fit to marginalized distributions (Youdin 2011)



Q1-Q16 Occurrence Rates



Q1-Q16 Occurrence Rates: Sensitivity Analysis

- Non-negligible systematic errors in planet occurrence rates exist when observational biases are not considered.
- The impact of inadequate star properties on planet occurrence rates is comparable to ignoring completeness and reliability.
- Resulting Occurrence Rate
 - 1 < Rp < 5 Re; 50 < Porb < 300 days</p>
 - 0.79 +/- 0.06 planets per star
 - Systematic range: 0.44 to 1.24
- Burke et al., in preparation

KEPLER .

Launched in 2009, has discovered thousands of planets around other stars

WFIRST-AFTA (Planned) Wide Field Infrared Survey Telescope – Astrophysics Focused Telescope Assets

Both likely to yield small sample statistics for the earth-analogs

Log Radius Distribution (periods less than 50 days) :

- Sharp rise at \sim 3 R_e
- Flat from 1-3 R_e

Log Period Distribution $(0.5 \text{ to } 22 \text{ R}_{e})$:

• Rises sharply but flattens out beyond 10 day orbits.

Average number of (R_p =0.8 to 1.25) planets per star: 16.5 ± 3.6%

I - 4 R_e

Period distribution (logarithmic) is flat from 10-200 days for small planets while giant planets are increasing in frequency.

Dong & Zhu 2012

- Independent transit detection pipeline applied to Q1-Q16 data
- ~42,000 (bright) G & K stars (4100-6100 K)
- Identified ~600 planet candidates
- Measured detection efficiency via transit injection

Petigura, Howard, & Marcy 2013

Average number of planets smaller than 1.4 R_e in the HZ of M dwarfs is 0.53 ± 0.17 (Dressing & Charbonneau 2013; Kopparapu 2013; Gaidos 2013)

22% of G & K dwarfs harbor a planet smaller than 2 R_e for HZ defined by 0.25 - 4 F_e (Petigura et al. 2013).

0.1

If the period distribution is flat across the blue shaded area, the occurrence rate will be the same in any equal area box contained within that region. Red box: 11%; Green box: 22%

Approximately 7% of G & K dwarfs harbor a planet with $R_p = 1$ to 1.4 R_e in the optimistic (empirical) HZ.

 $R_p = 0.5$ to 1.4 R_e in the optimistic (empirical) HZ.

Kepter Stellar Density vs. Transit Duration

Transit Injection Tests

Knowledge of catalog reliability

Globally averaged, the false positive rate (FPR) is less than 15% but is highly dependent on planet properties.

Empirical measurements yield FPR=35% for the close-in giant exoplanets and < 5% for super-earths.