

# Corrections

## BIOPHYSICS AND COMPUTATIONAL BIOLOGY

Correction for “Mechanism of E-cadherin dimerization probed by NMR relaxation dispersion,” by Ying Li, Nicole L. Altorelli, Fabiana Bahna, Barry Honig, Lawrence Shapiro, and Arthur G. Palmer III, which appeared in issue 41, October 8, 2013, of *Proc Natl Acad Sci USA* (110:16462–16467; first published September 25, 2013; 10.1073/pnas.1314303110).

The authors note that the second sentence in the Acknowledgments, “This work was supported by National Institutes of Health (NIH) Grants GM059273 (to A.G.P.) and GM062270 (to L.S.)” should instead appear as “This work was supported by National Institutes of Health (NIH) Grants GM059273 (to A.G.P.) and GM062270 (to L.S.) and by National Science Foundation Grant MCB-0918535 (to B.H.)”

[www.pnas.org/cgi/doi/10.1073/pnas.1319465110](http://www.pnas.org/cgi/doi/10.1073/pnas.1319465110)

## DEVELOPMENTAL BIOLOGY

Correction for “A Hox gene controls lateral line cell migration by regulating chemokine receptor expression downstream of Wnt signaling,” by Marie A. Breau, David G. Wilkinson, and Qiling Xu, which appeared in issue 42, October 15, 2013, of *Proc Natl Acad Sci USA* (110:16892–16897; first published September 30, 2013; 10.1073/pnas.1306282110).

The authors note that, due to a printer’s error, refs. 33–38 were numbered incorrectly. The citations to the reference numbers are correct in the text. Below is the correct order for refs. 33–38.

33. Gamba L, Cubedo N, Ghysen A, Lutfalla G, Dambly-Chaudière C (2010) Estrogen receptor ESR1 controls cell migration by repressing chemokine receptor CXCR4 in the zebrafish posterior lateral line system. *Proc Natl Acad Sci USA* 107(14):6358–6363.
34. Westerfield M (1993) *The Zebrafish Book* (Univ of Oregon Press, Eugene).
35. Kwan KM, et al. (2007) The Tol2kit: A multisite gateway-based construction kit for Tol2 transposon transgenesis constructs. *Dev Dyn* 236(11):3088–3099.
36. Xu Q, Wilkinson DG (1998) *In situ hybridization of mRNA with hapten labelled probes. In Situ Hybridization: A Practical Approach*, ed Wilkinson DG (Oxford Univ Press, Oxford), 2nd Ed, pp 87–106.
37. Robu ME, et al. (2007) p53 activation by knockdown technologies. *PLoS Genet* 3(5):e78.
38. Gerety SS, Wilkinson DG (2011) Morpholino artifacts provide pitfalls and reveal a novel role for pro-apoptotic genes in hindbrain boundary development. *Dev Biol* 350(2):279–289.

[www.pnas.org/cgi/doi/10.1073/pnas.1319266110](http://www.pnas.org/cgi/doi/10.1073/pnas.1319266110)

## IMMUNOLOGY

Correction for “IFI16 senses DNA forms of the lentiviral replication cycle and controls HIV-1 replication,” by Martin R. Jakobsen, Rasmus O. Bak, Annika Andersen, Randi K. Berg, Søren B. Jensen, Jin Tengchuan, Anders Laustsen, Kathrine Hansen, Lars Østergaard, Katherine A. Fitzgerald, T. Sam Xiao, Jacob G. Mikkelsen, Trine H. Mogensen, and Søren R. Paludan, which appeared in issue 48, November 26, 2013, of *Proc Natl Acad Sci USA* (110:E4571–E4580; first published October 23, 2013; 10.1073/pnas.1311669110).

The authors note that the author name Jin Tengchuan should instead appear as Tengchuan Jin. The corrected author line appears below. The online and print versions have been corrected.

**Martin R. Jakobsen, Rasmus O. Bak, Annika Andersen, Randi K. Berg, Søren B. Jensen, Tengchuan Jin, Anders Laustsen, Kathrine Hansen, Lars Østergaard, Katherine A. Fitzgerald, T. Sam Xiao, Jacob G. Mikkelsen, Trine H. Mogensen, and Søren R. Paludan**

[www.pnas.org/cgi/doi/10.1073/pnas.1320190110](http://www.pnas.org/cgi/doi/10.1073/pnas.1320190110)

## MATHEMATICS

Correction for “Violating the Shannon capacity of metric graphs with entanglement,” by Jop Briët, Harry Buhrman, and Dion Gijswijt, which appeared in issue 48, November 26, 2013, of *Proc Natl Acad Sci USA* (110:19227–19232; first published December 24, 2012; 10.1073/pnas.1203857110).

The authors note that, due to a printer’s error, on page 19227, left column, first full paragraph, line 6 “ $G_n$ ” should instead appear as “ $a \in R$ ”.

Also, on page 19227, left column, first full paragraph, line 7 “ $x \in V(H_n)$ ” should instead appear as “ $x \in S$ ”. Both the online article and the print article have been corrected.

[www.pnas.org/cgi/doi/10.1073/pnas.1301191110](http://www.pnas.org/cgi/doi/10.1073/pnas.1301191110)

## ASTRONOMY

Correction for “Prevalence of Earth-size planets orbiting Sun-like stars,” by Erik A. Petigura, Andrew W. Howard, and Geoffrey W. Marcy, which appeared in issue 48, November 26, 2013, of *Proc Natl Acad Sci USA* (110:19273–19278; first published November 4, 2013; 10.1073/pnas.1319909110).

The authors note that the following statement should be added as a Note Added in Proof: “Estimates of the occurrence of Earth analog planets appear in several previous works including Catanzarite and Shao (25), Traub (26), and Dong and Zhu (27). These estimates, which range from 1% to 34%, were built upon early catalogs of *Kepler* planet candidates (based on less than 1.3 years of photometry). These estimates did not address survey completeness with injection and recovery or uncertain stellar radii with spectroscopy.” The online version has been updated to include the following three references:

25. Catanzarite J, Shao M (2011) The occurrence rate of earth analog planets orbiting sun-like stars. *Astrophys J* 738(2):151–160.
26. Traub W (2012) Terrestrial, habitable-zone exoplanet frequency from Kepler. *Astrophys J* 745(1):20–29.
27. Dong S, Zhu Z (2013) Fast rise of “Neptune-size” planets (4–8  $R_{\text{Earth}}$ ) from  $P \sim 10$  to  $\sim 250$  days—Statistics of Kepler planet candidates up to  $\sim 0.75$  AU. *Astrophys J* 778(1): 53–63.

[www.pnas.org/cgi/doi/10.1073/pnas.1321363110](http://www.pnas.org/cgi/doi/10.1073/pnas.1321363110)

# Prevalence of Earth-size planets orbiting Sun-like stars

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Contributed by Geoffrey W. Marcy, October 22, 2013 (sent for review October 18, 2013)

Determining whether Earth-like planets are common or rare looms as a touchstone in the question of life in the universe. We searched for Earth-size planets that cross in front of their host stars by examining the brightness measurements of 42,000 stars from National Aeronautics and Space Administration's *Kepler* mission. We found 603 planets, including 10 that are Earth size ( $1-2 R_{\oplus}$ ) and receive comparable levels of stellar energy to that of Earth ( $0.25-4 F_{\oplus}$ ). We account for *Kepler*'s imperfect detectability of such planets by injecting synthetic planet-caused dimmings into the *Kepler* brightness measurements and recording the fraction detected. We find that  $11 \pm 4\%$  of Sun-like stars harbor an Earth-size planet receiving between one and four times the stellar intensity as Earth. We also find that the occurrence of Earth-size planets is constant with increasing orbital period ( $P$ ), within equal intervals of  $\log P$  up to  $\sim 200$  d. Extrapolating, one finds  $5.7^{+1.7}_{-2.2}\%$  of Sun-like stars harbor an Earth-size planet with orbital periods of 200–400 d.

extrasolar planets | astrobiology

The National Aeronautics and Space Administration's (NASA's) *Kepler* mission was launched in 2009 to search for planets that transit (cross in front of) their host stars (1–4). The resulting dimming of the host stars is detectable by measuring their brightness, and *Kepler* monitored the brightness of 150,000 stars every 30 min for 4 y. To date, this exoplanet survey has detected more than 3,000 planet candidates (4).

The most easily detectable planets in the *Kepler* survey are those that are relatively large and orbit close to their host stars, especially those stars having lower intrinsic brightness fluctuations (noise). These large, close-in worlds dominate the list of known exoplanets. However, the *Kepler* brightness measurements can be analyzed and debiased to reveal the diversity of planets, including smaller ones, in our Milky Way Galaxy (5–7). These previous studies showed that small planets approaching Earth size are the most common, but only for planets orbiting close to their host stars. Here, we extend the planet survey to *Kepler*'s most important domain: Earth-size planets orbiting far enough from Sun-like stars to receive a similar intensity of light energy as Earth.

## Planet Survey

We performed an independent search of *Kepler* photometry for transiting planets with the goal of measuring the underlying occurrence distribution of planets as a function of orbital period,  $P$ , and planet radius,  $R_p$ . We restricted our survey to a set of Sun-like stars (GK type) that are the most amenable to the detection of Earth-size planets. We define GK-type stars as those with surface temperatures  $T_{\text{eff}} = 4,100-6,100$  K and gravities  $\log g = 4.0-4.9$  ( $\log g$  is the base 10 logarithm of a star's surface gravity measured in  $\text{cm s}^{-2}$ ) (8). Our search for planets was further restricted to the brightest Sun-like stars observed by *Kepler* ( $Kp = 10-15$  mag). These 42,557 stars (Best42k) have the lowest photometric noise, making them amenable to the detection of Earth-size planets. When a planet crosses in front of its star, it causes a fractional dimming that is proportional to the fraction of the stellar disk blocked,  $\delta F = (R_p/R_*)^2$ , where  $R_*$  is the radius of the star. As viewed by a distant observer, the Earth dims the Sun by  $\sim 100$  parts per million (ppm) lasting 12 h every 365 d.

We searched for transiting planets in *Kepler* brightness measurements using our custom-built TERRA software package described in previous works (6, 9) and in *SI Appendix*. In brief, TERRA conditions *Kepler* photometry in the time domain, removing outliers, long timescale variability ( $>10$  d), and systematic errors common to a large number of stars. TERRA then searches for transit signals by evaluating the signal-to-noise ratio (SNR) of prospective transits over a finely spaced 3D grid of orbital period,  $P$ , time of transit,  $t_0$ , and transit duration,  $\Delta T$ . This grid-based search extends over the orbital period range of 0.5–400 d.

TERRA produced a list of "threshold crossing events" (TCEs) that meet the key criterion of a photometric dimming SNR ratio  $\text{SNR} > 12$ . Unfortunately, an unwieldy 16,227 TCEs met this criterion, many of which are inconsistent with the periodic dimming profile from a true transiting planet. Further vetting was performed by automatically assessing which light curves were consistent with theoretical models of transiting planets (10). We also visually inspected each TCE light curve, retaining only those exhibiting a consistent, periodic, box-shaped dimming, and rejecting those caused by single epoch outliers, correlated noise, and other data anomalies. The vetting process was applied homogeneously to all TCEs and is described in further detail in *SI Appendix*.

To assess our vetting accuracy, we evaluated the 235 *Kepler* objects of interest (KOIs) among Best42k stars having  $P > 50$  d, which had been found by the *Kepler* Project and identified as planet candidates in the official Exoplanet Archive ([exoplanetarchive.ipac.caltech.edu](http://exoplanetarchive.ipac.caltech.edu); accessed 19 September 2013). Among them, we found four whose light curves are not consistent with being planets. These four KOIs (364.01, 2,224.02, 2,311.01, and 2,474.01) have long periods and small radii (*SI Appendix*). This exercise suggests that our vetting process is robust and that careful scrutiny of the light curves of small planets in long period orbits is useful to identify false positives.

## Significance

A major question is whether planets suitable for biochemistry are common or rare in the universe. Small rocky planets with liquid water enjoy key ingredients for biology. We used the National Aeronautics and Space Administration *Kepler* telescope to survey 42,000 Sun-like stars for periodic dimmings that occur when a planet crosses in front of its host star. We found 603 planets, 10 of which are Earth size and orbit in the habitable zone, where conditions permit surface liquid water. We measured the detectability of these planets by injecting synthetic planet-caused dimmings into *Kepler* brightness measurements. We find that 22% of Sun-like stars harbor Earth-size planets orbiting in their habitable zones. The nearest such planet may be within 12 light-years.

Author contributions: E.A.P., A.W.H., and G.W.M. designed research, performed research, analyzed data, and wrote the paper.

The authors declare no conflict of interest.

Freely available online through the PNAS open access option.

Data deposition: The *Kepler* photometry is available at the Mikulski Archive for Space Telescopes ([archive.stsci.edu](http://archive.stsci.edu)). All spectra are available to the public on the Community Follow-up Program website ([cfop.ipac.caltech.edu](http://cfop.ipac.caltech.edu)).

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This article contains supporting information online at [www.pnas.org/lookup/suppl/doi:10.1073/pnas.1319909110/-DCSupplemental](http://www.pnas.org/lookup/suppl/doi:10.1073/pnas.1319909110/-DCSupplemental).

Vetting of our TCEs produced a list of 836 eKOIs, which are analogous to KOIs produced by the *Kepler* Project. Each light curve is consistent with an astrophysical transit but could be due to an eclipsing binary (EB), either in the background or gravitationally bound, instead of a transiting planet. If an EB resides within the software aperture of a *Kepler* target star (within  $\sim 10$  arcsec), the dimming of the EB can masquerade as a planet transit when diluted by the bright target star. We rejected as likely EBs any eKOIs with these characteristics: radii larger than  $20 R_{\oplus}$ , observed secondary eclipse, or astrometric motion of the target star in and out of transit (*SI Appendix*). This rejection of EBs left 603 eKOIs in our catalog.

*Kepler* photometry can be used to measure  $R_p/R_*$  with high precision, but the extraction of planet radii is compromised by poorly known radii of the host stars (11). To determine  $R_*$  and  $T_{\text{eff}}$ , we acquired high-resolution spectra of 274 eKOIs using the HIRES spectrometer on the 10-m Keck I telescope. Notably, we obtained spectra of all 62 eKOIs that have  $P > 100$  d. For these stars, the  $\sim 35\%$  errors in  $R_*$  were reduced to  $\sim 10\%$  by matching spectra to standards.

To measure planet occurrence, one must not only detect planets but also assess what fraction of planets were missed. Missed planets are of two types: those whose orbital planes are so tilted as to avoid dimming the star and those whose transits were not detected in the photometry by TERRA. Both effects can be quantified to establish a statistical correction factor. The first correction can be computed as the geometrical probability that an orbital plane is viewed edge-on enough (from Earth) that the planet transits the star. This probability is  $P_T = R_*/a$ , where  $a$  is the semimajor axis of the orbit.

The second correction is computed by the injection and recovery of synthetic (mock) planet-caused dimmings into real *Kepler* photometry. We injected 40,000 transit-like synthetic dimmings having randomly selected planetary and orbital properties into the actual photometry of our Best42k star sample, with stars selected at random. We measured survey completeness,  $C(P, R_p)$ , in small bins of  $(P, R_p)$ , determining the fraction of injected synthetic planets that were discovered by TERRA (*SI Appendix*). Fig. 1 shows the 603 detected planets and the survey completeness,  $C$ , color-coded as a function of  $P$  and  $R_p$ .

The survey completeness for small planets is a complicated function of  $P$  and  $R_p$ . It decreases with increasing  $P$  and decreasing

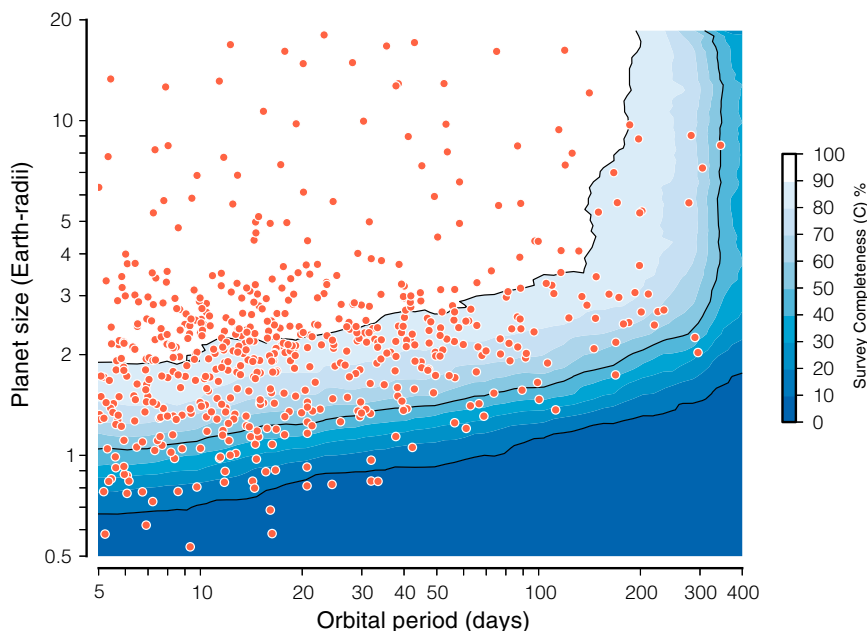
$R_p$  as expected due to fewer transits and less dimming, respectively. It is dangerous to replace this injection and recovery assessment with noise models to determine  $C$ . Such models are not sensitive to the absolute normalization of  $C$  and only provide relative completeness. Models also may not capture the complexities of a multistage transit-finding pipeline that is challenged by correlated, nonstationary, and non-Gaussian noise. Measuring the occurrence of small planets with long periods requires injection and recovery of synthetic transits to determine the absolute detectability of the small signals buried in noise.

## Planet Occurrence

We define planet occurrence,  $f$ , to be the fraction of stars having a planet within a specified range of orbital period, size, and perhaps other criteria. We report planet occurrence as a function of planet size and orbital period,  $f(P, R_p)$  and as a function of planet size and the stellar light intensity (flux) incident on the planet,  $f(F_p, R_p)$ .

**Planet Occurrence and Orbital Period.** We computed  $f(P, R_p)$  in a  $6 \times 4$  grid of  $P$  and  $R_p$  shown in Fig. 2. We start by first counting the number of detected planets,  $n_{\text{cell}}$ , in each  $P$ - $R_p$  cell. Then we computed  $f(P, R_p)$  by making statistical corrections for planets missed because of nontransiting orbital inclinations and because of the completeness factor,  $C$ . The first correction augments each detected transiting planet by  $1/P_T = a/R_*$ , where  $P_T$  is the geometric transit probability, to account for planets missed in inclined orbits. Accounting for the completeness,  $C$ , the occurrence in a cell is  $f(P, R_p) = 1/n_* \sum_i a_i / (R_{*i} C_i)$ , where  $n_* = 42,557$  stars, and the sum is over all detected planets within that cell. Uncertainties in the statistical corrections for  $a/R_*$  and for completeness may cause errors in the final occurrence rates of  $\sim 10\%$ . Such errors will be smaller than the Poisson uncertainties in the occurrence of Earth-size planets in long period orbits.

Fig. 2 shows the occurrence of planets,  $f(P, R_p)$ , within the  $P$ - $R_p$  plane. Each cell is color-coded to indicate the final planet occurrence: the fraction of stars having a planet with radius and orbital period corresponding to that cell (after correction for both completeness factors). For example,  $7.7 \pm 1.3\%$  of Sun-like stars have a planet with periods between 25 and 50 d and sizes between 1 and  $2 R_{\oplus}$ .



**Fig. 1.** 2D domain of orbital period and planet size, on a logarithmic scale. Red circles show the 603 detected planets in our survey of 42,557 bright Sun-like stars ( $K_p = 10$ –15 mag, GK spectral type). The color scale shows survey completeness measured by injection and recovery of synthetic planets into real photometry. Dark regions represent  $(P, R_p)$  with low completeness,  $C$ , where significant corrections for missed planets must be made to compute occurrence. The most common planets detected have orbital  $P < 20$  d and  $R_p \approx 1$ – $3 R_{\oplus}$  (at middle left of graph). However, their detectability is favored by orbital tilt and detection completeness,  $C$ , that favors detection of such close-in, large planets.

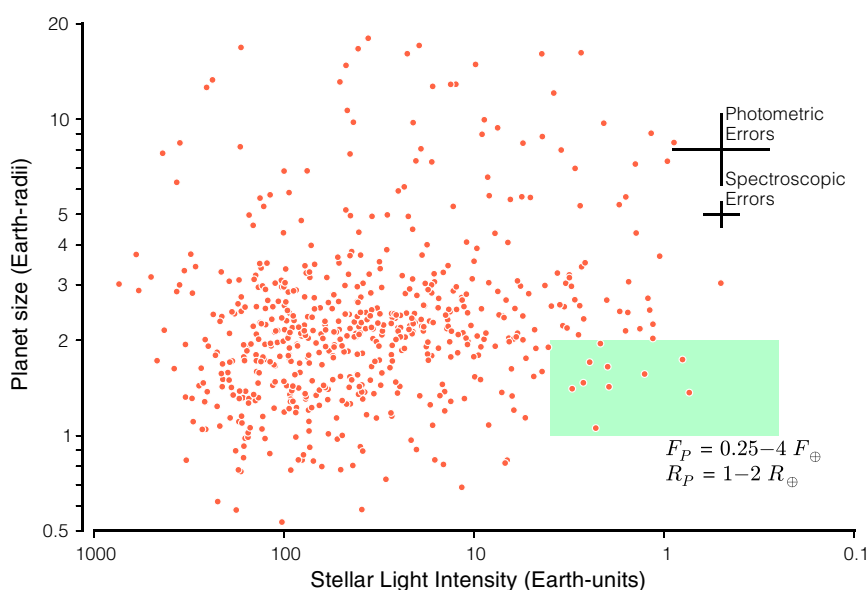


these second and third transiting planets boosts the total number of planets per cell (and hence the occurrence) by 21–28% over the  $P = 50\text{--}400$  d,  $R_p = 1\text{--}4 R_\oplus$  domain (SI Appendix).

Even with our careful vetting of eKOIs, the light curves of some false-positive scenarios are indistinguishable from planets. Fressin et al. (7) simulated the contamination of a previous KOI (4) sample by false positives that were not removed by the *Kepler* Project vetting process. They determined that the largest source of false positives for Earth-size planets are physically bound stars with a transiting Neptune-size planet, with an overall false-positive rate of 8.8–12.3%. As we have shown (Fig. 2), the occurrence of Neptune-size planets is nearly constant as a function of orbital period, in  $\log P$  intervals. Thus, this false-positive rate is also nearly constant in period. Therefore, we adopt a 10% false-positive rate for planets having  $P = 50\text{--}400$  d and  $R_p = 1\text{--}2 R_\oplus$ . Planet occurrence, shown in Figs. 2 and 3, has not been adjusted to account for false positives or planet multiplicity. The quoted errors reflect only binomial counting uncertainties. Note that for Earth-size planets in the 50–100 and 100–200 d period bins, planet occurrence is  $5.8 \pm 1.8\%$  and  $3.2 \pm 1.6\%$ , respectively. Corrections due to false positives or planet multiplicity are smaller than fractional uncertainties due to small number statistics.

**Planet Occurrence and Stellar Light Intensity.** The amount of light energy a planet receives from its host star depends on the luminosity of the star ( $L_*$ ) and the planet-star separation ( $a$ ). Stellar light flux,  $F_p$ , is given by  $F_p = L_*/4\pi a^2$ . The intensity of sunlight on Earth is  $F_\oplus = 1.36 \text{ kW m}^{-2}$ . We compute  $L_*$  using  $L_* = 4\pi R_*^2 \sigma T_{\text{eff}}^4$ , where  $\sigma = 5.670 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$  is the Stefan-Boltzmann constant. The dominant uncertainty in  $F_p$  is due to  $R_*$ . Using spectroscopic stellar parameters, we determine  $F_p$  to 25% accuracy and to 80% accuracy using photometric parameters. We obtained spectra for all 62 stars hosting planets with  $P > 100$  d, allowing more accurate light intensity measurements.

Fig. 4 shows the 2D domain of stellar light flux incident on our 603 detected planets, along with planet size. The planets in our sample receive a wide range of flux from their host stars, ranging from 0.5 to 700  $F_\oplus$ . We highlight the 10 small ( $R_p = 1\text{--}2 R_\oplus$ ) planets that receive stellar flux comparable to Earth:  $F_p = 0.25\text{--}4 F_\oplus$ .



**Fig. 4.** The detected planets (dots) in a 2D domain similar to Figs. 1 and 2. Here, the 2D domain has orbital period replaced by stellar light intensity, incident flux, hitting the planet. The highlighted region shows the 10 Earth-size planets that receive an incident stellar flux comparable to the Earth: flux = 0.25–4.0 times the flux received by the Earth from the Sun. Our uncertainties on stellar flux and planet radii are indicated at the top right.

Because only two  $1\text{--}2 R_\oplus$  planets have  $F_p < 1 F_\oplus$ , we measure planet occurrence in the domain,  $1\text{--}2 R_\oplus$  and  $1\text{--}4 F_\oplus$ . Correcting for survey completeness, we find that  $11 \pm 4\%$  of Sun-like stars have a  $R_p = 1\text{--}2 R_\oplus$  planet that receives between one and four times the incident flux as the Earth (SI Appendix).

### Interpretation

**Earth-Size Planets with Year-Long Orbital Periods.** Detections of Earth-size planets having orbital periods of  $P = 200\text{--}400$  d are expected to be rare in this survey. Low survey completeness ( $C \approx 10\%$ ) and low transit probability ( $P_T = 0.5\%$ ) imply that only a few such planets would be expected, even if they are intrinsically common. Indeed, we did not detect any such planets with TERRA, although the radii of three planets (KIC-4478142, KIC-8644545, and KIC-10593626) have  $1\sigma$  confidence intervals that extend into the  $P = 200\text{--}400$  d,  $R_p = 1\text{--}2 R_\oplus$  domain. We can place an upper limit on their occurrence:  $f < 12\%$  with 95% confidence using binomial statistics. We would have detected one or two such planets if their occurrence was higher than 12%.

However, one may estimate the occurrence of  $1\text{--}2 R_\oplus$  planets with periods of 200–400 d by a modest extrapolation of planet occurrence with  $P$ . Fig. 5 shows the fraction of stars with  $1\text{--}2 R_\oplus$  planets, whose orbital period is less than a maximum period,  $P$ , on the horizontal axis. This cumulative period distribution shows that 20.4% of Sun-like stars harbor a  $1\text{--}2 R_\oplus$  planet with an orbital period,  $P < 50$  d. Similarly, 26.2% of Sun-like stars harbor a  $1\text{--}2 R_\oplus$  planet with a period less than 100 d. The linear increase in cumulative occurrence implies constant planet occurrence per  $\log P$  interval. Extrapolating the cumulative period distribution predicts  $5.7^{+1.7}_{-2.2}\%$  occurrence of Earth-size ( $1\text{--}2 R_\oplus$ ) planets with orbital periods of  $\sim 1$  y ( $P = 200\text{--}400$  d). The details of our extrapolation technique are explained in SI Appendix. Extrapolation based on detected planets with  $P < 200$  d predicts that  $5.7^{+1.7}_{-2.2}\%$  of Sun-like stars have an Earth-size planet on an Earth-like orbit ( $P = 200\text{--}400$  d).

Naturally, such an extrapolation carries less weight than a direct measurement. However, the loss of *Kepler's* second reaction wheel in May 2013 ended observations shortly after the completion of the nominal 3.5-y mission. We cannot count on any additional *Kepler* data to improve the low completeness to Earth



One may adopt alternative definitions of both the properties of Earth-size planets and the domain of the HZ. We showed previously that the occurrence of planets is approximately constant as a function of both  $R_P$  (for  $R_P < 2.8 R_\oplus$ ) and  $P$  (in logarithmic intervals). Thus, the occurrence of planets in this domain is proportional to logarithmic area in the  $R_P$ - $F_P$  parameter space being considered. For example, the occurrence of planets of size  $1.0$ – $1.4 R_\oplus$  in orbits that receive  $0.25$ – $1.0 F_\oplus$  in stellar flux is  $22\%/4 = 5.5\%$ . We offer a number of estimates for the prevalence of Earth-size planets in the HZ based on different published definitions of the HZ in Table 1.

Cooler, M dwarf stars also have a high occurrence of Earth-size planets. Based on the *Kepler* planet catalog, Dressing et al. (19) found that  $15^{+15}_{-6}\%$  of early M dwarfs have an Earth-size planet ( $0.5$ – $1.4 R_\oplus$ ) in the HZ using a conservative definition of  $0.5$ – $1.1 F_\oplus$  (15) and three times that value when the HZ is expanded to  $0.25$ – $1.5 F_\oplus$  (20). This result is consistent with a Doppler survey that found that  $41^{+54}_{-13}\%$  of nearby M dwarfs have planets with masses  $1$ – $10$  Earth masses ( $M_\oplus$ ) in the HZ (21). Thus, Earth-size planets appear to be common in the HZs of a range of stellar types.

## Conclusions

Using *Kepler* photometry of Sun-like stars (GK-type), we measured the prevalence of planets having different orbital periods and sizes, down to the size of the Earth and out to orbital periods of 1 y. We gathered Keck spectra of all host stars of planets having periods greater than 100 d to accurately determine their radii. The detection of planets with periods longer than 100 d is challenging, and we characterized our sensitivity to such planets by using injection and recovery of synthetic planets in the photometry. After correcting for orbital tilt and detection completeness, we find that  $26 \pm 3\%$  of Sun-like stars have an Earth-size ( $1$ – $2 R_\oplus$ ) planet with  $P = 5$ – $100$  d. We also find that  $11 \pm 4\%$  of Sun-like stars harbor an Earth-size planet that receives nearly Earth levels of stellar energy ( $F_P = 1$ – $4 F_\oplus$ ).

We showed that small planets far outnumber large ones. Only  $1.6 \pm 0.4\%$  of Sun-like stars harbor a Jupiter-size ( $8$ – $16 R_\oplus$ ) planet with  $P = 5$ – $100$  d compared with a  $23 \pm 3\%$  occurrence of Earth-size planets. This pattern supports the core accretion scenario in which planets form by the accumulation of solids first and gas later in the protoplanetary disk (13, 22–24). The details of this family of models are hotly debated, including the movement of material within the disk, the timescale for planet formation, and the amount of gas accretion in small planets.

Our measurement of a constant occurrence of  $1$ – $2.8 R_\oplus$  planets per  $\log P$  interval establishes an important observational constraint for these models.

The occurrence of Earth-size planets is constant with decreasing stellar light intensity from  $100 F_\oplus$  down to  $1 F_\oplus$ . If one was to assume that this pattern continues down to  $0.25 F_\oplus$ , then the occurrence of planets having flux levels of  $1$ – $0.25 F_\oplus$  is also  $11 \pm 4\%$ .

Earth-size planets are common in the *Kepler* field. If the stars in the *Kepler* field are representative of stars in the solar neighborhood, then Earth-size planets are common around nearby Sun-like stars. If one were to adopt a  $22\%$  occurrence rate of Earth-size planets in habitable zones of Sun-like stars, then the nearest such planet is expected to orbit a star that is less than 12 light-years from Earth and can be seen by the unaided eye. Future instrumentation to image and take spectra of these Earths need only observe a few dozen nearby stars to detect a sample of Earth-size planets residing in the HZs of their host stars.

**Note Added in Proof.** Estimates of the occurrence of Earth analog planets appear in several previous works including Catanzarite and Shao (25), Traub (26), and Dong and Zhu (27). These estimates, which range from  $1\%$  to  $34\%$ , were built upon early catalogs of *Kepler* planet candidates (based on less than 1.3 years of photometry). These estimates did not address survey completeness with injection and recovery or uncertain stellar radii with spectroscopy.

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- Borucki WJ, et al. (2010) *Kepler* planet-detection mission: Introduction and first results. *Science* 327(5968):977–980.
- Koch DG, et al. (2010) *Kepler* mission design, realized photometric performance, and early science. *Astrophys J Lett* 713(2):L79–L86.
- Borucki WJ, et al. (2011) Characteristics of planetary candidates observed by *Kepler*. II. Analysis of the first four months of data. *Astrophys J* 736(1):19–40.
- Batalha NM, et al. (2013) Planetary candidates observed by *Kepler*. III. Analysis of the first 16 months of data. *Astrophys J* 204(2):24–44.
- Howard AW, et al. (2012) Planet occurrence within 0.25 AU of solar-type stars from *Kepler*. *Astrophys J* 201(2):15–39.
- Petigura EA, Marcy GW, Howard AW (2013) A plateau in the planet population below twice the size of Earth. *Astrophys J* 770(1):69–89.
- Fressin F, et al. (2013) The false positive rate of *Kepler* and the occurrence of planets. *Astrophys J* 766(2):81–100.
- Pinsonneault MH, et al. (2012) A revised effective temperature scale for the *Kepler* input catalog. *Astrophys J* 199(2):30–51.
- Petigura EA, Marcy GW (2012) Identification and removal of noise modes in *Kepler* photometry. *Publ Astron Soc Pac* 124(920):1073–1082.
- Mandel K, Agol E (2002) Analytic light curves for planetary transit searches. *Astrophys J Lett* 580(2):L171–L175.
- Brown TM, Latham DW, Everett ME, Esquerdo GA (2011) *Kepler* input catalog: Photometric calibration and stellar classification. *Astron J* 142(4):112–129.
- Youdin AN (2011) The exoplanet census: A general method applied to *Kepler*. *Astrophys J* 742(1):38–50.
- Ida S, Lin DNC, Nagasawa M (2013) Toward a deterministic model of planetary formation. VII. Eccentricity distribution of gas giants. *Astrophys J* 775(1):42–64.
- Seager S (2013) Exoplanet habitability. *Science* 340(6132):577–581.
- Kasting JF, Whitmire DP, Reynolds RT (1993) Habitable zones around main sequence stars. *Icarus* 101(1):108–128.
- Kopparapu RK, et al. (2013) Habitable zones around main-sequence stars: New estimates. *Astrophys J* 765(2):131–146.
- Zsom A, Seager S, de Wit J, Stamenkovic V Towards the minimum inner edge distance of the habitable zone *Astrophys J* 778(2):109.
- Pierrehumbert R, Gaidos E (2011) Hydrogen greenhouse planets beyond the habitable zone. *Astrophys J Lett* 734(1):L13–L17.
- Dressing CD, Charbonneau D (2013) The occurrence rate of small planets around small stars. *Astrophys J* 767(1):95–114.
- Kopparapu RK (2013) A revised estimate of the occurrence rate of terrestrial planets in the habitable zones around *Kepler* M-dwarfs. *Astrophys J Lett* 767(1):L8–L12.
- Bonfils X, et al. (2013) The HARPS search for southern extra-solar planets. XXXI. The M-dwarf sample. *Astron Astrophys* 549:A109.
- Levy EH, Lunine JI, eds (1993) *Growth of Planets from Planetesimals* (University of Arizona Press, Tucson, AZ), pp 1061–1088.
- Pollack JB, et al. (1996) Formation of the giant planets by concurrent accretion of solids and gas. *Icarus* 124(1):62–85.
- Mordasini C, et al. (2012) Characterization of exoplanets from their formation. II. The planetary mass-radius relationship. *Astron Astrophys* 547:A112.
- Catanzarite J, Shao M (2011) The occurrence rate of earth analog planets orbiting sun-like stars. *Astrophys J* 738(2):151–160.
- Traub W (2012) Terrestrial, habitable-zone exoplanet frequency from *Kepler*. *Astrophys J* 745(1):20–29.
- Dong S, Zhu Z (2013) Fast rise of “Neptune-size” planets (4–8  $R_{\text{Earth}}$ ) from  $P \sim 10$  to  $\sim 250$  days—Statistics of *Kepler* planet candidates up to  $\sim 0.75$  AU. *Astrophys J* 778(1):53–63.