Revised estimates of the frequency of Earth-like planets in the Kepler field

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Abstract. The search for Earth-like planets around Sun-like stars and the evaluation of their occurrence rate is a major topic of research for the exoplanetary community. Two key characteristics in defining a planet as 'Earth-like' are having a radius between 1 and 1.75 times the Earth's radius and orbiting inside the host star's habitable zone; the measurement of the planet's radius and related error is however possible only via transit observations and is highly dependent on the precision of the host star's radius. A major improvement in the determination of stellar radius is represented by the unprecedented precision on parallax measurements provided by the Gaia astrometry satellite. We present a new estimate of the frequency of Earth-sized planets orbiting inside the host stars's habitable zones, obtained using Gaia measurements of parallax for solar-type stars hosting validated planets in the Kepler field as input for reassessing the values of planetary radius and incident stellar flux. This updated occurrence rate can usefully inform future observational efforts searching for Earth-like systems in the Sun backyard using a variety of techniques such as the spectrograph ESPRESSO, the space observatory PLATO and the proposed astrometric satellite Theia.

Keywords. astrometry, planetary systems, methods: statistical

1. Introduction

A major point of interest in the search for extrasolar planets is represented by the determination of the frequency of planetary bodies that may be defined as Earth-like, a term commonly referring to small rocky planets similar in size to the Earth and orbiting Sun-like stars at a distance suitable for the presence of liquid water on their surface. While the exact boundaries in planetary radius and incident stellar flux that may characterize an exoplanet as Earth-like are subject to debate and represent an important point in the study of planetary populations and evolution, previous studies provide helpful insights on the occurrence of this planetary class.

A key study in the determination of frequency of Earth-like planets around Sun-like stars ($\eta_\oplus$) is represented by Petigura et al. (2013), in which bright Sun-like stars (here defined as having Kepler magnitude between 10 and 15 mag, $T_{\text{eff}}$ between 4100 and 6100 K and surface gravity log $g$ between 4.0 and 4.9) in the Kepler catalogue were searched for Earth-like transits, using as defining boundaries planetary radii between 1.0 and 2.0 $R_\oplus$ and incident fluxes between 0.25 and 4 $F_\oplus$. Amongst the 42557 Sun-like stars selected by the study a total of 10 Earth-like planets were found, resulting in an estimate of potentially habitable Earths frequency of $\eta_\oplus = 22 \pm 8\%$. However, it is clear that the determination of the size of a transiting planet, and in turn its characterization as Earth-like or otherwise, is highly dependent on the precision of the host star's radius.

Since the publication of Petigura et al. (2013) however, the launch and operation of
the astrometric mission Gaia (Gaia Collaboration (2016)) allowed for the determination of parallaxes at unprecedented precision for over a billion stars, allowing for more precise assessment of stellar radii and in turn of transiting planets radii. For example, the use of precise radius measurements from both the California-Kepler Survey and Gaia DR2 detailed in Fulton et al. (2017) and Fulton & Petigura (2018) show that the distribution of small ($R_p < 4R_\oplus$) planets features a significant gap at about $1.75R_\oplus$, separating the observed small planet distribution into two different classes, namely rocky super-Earths (below $1.75R_\oplus$) and gas-dominated sub-Neptunes (above $1.75R_\oplus$), the gap being interpreted as the result of photoevaporation of low-density atmospheric envelopes.

In a further example of how Gaia astrometric measurements help in characterizing stellar hosts and transiting planets, in Berger et al. (2018) the crossmatching between DR2 and Kepler catalogues and the use of isochrone evolutionary models with Gaia parallaxes as inputs allow new derivation of stellar radii for 177911 stars in the Kepler field, from which new values of the planetary radii and incident fluxes of 2123 confirmed and 1922 candidate exoplanets are obtained. From this, a first important result is represented by the typical precision on the newly derived stellar radii of $\sim8\%$, about 5 times lower than previous estimates in the DR25 Kepler Stellar Properties Catalog. In addition to this, the authors of the cited work confirm the aforementioned gap in the planetary radius distribution, while suggesting that said gap lies at about $1.94R_\oplus$, a slightly higher value than the one reported in the previous studies but still consistent to $1\sigma$. Finally, Berger et al. (2018) find 30 planet candidates and 8 confirmed planets with new estimates of radius $< 2R_\oplus$ and incident flux between 0.25 and 1.50 $F_\oplus$ and therefore considered to be rocky planets in their host star’s habitable zone.

In this work we use the latest values of stellar parallax and radii from the Gaia Second Data Release (DR2, see Gaia Collaboration (2018)) to provide an updated assessment of the value of Earth-like planetary occurrence $\eta_\oplus$ to compare with the literature results and to show that, although the astrometric amplitude of an Earth-like planet will remain well below the end-of-mission accuracy of Gaia, DR2 and future astrometric data can still be instrumental in better characterizing host stars and in turn transiting terrestrial planets, further fuel the search for potentially habitable rocky planets in the Milky Way.

2. Stellar and planetary radii in the Kepler field from DR2

For the purposes of our work, we choose to focus on a subset of the 177911 stars for which Berger et al. (2018) derived new values of stellar radii using Gaia DR2 parallaxes, namely the subset of Sun-like stars with physical parameters lying inside the boundaries already used in Petigura et al. (2013) ($T_{\text{eff}} = 4100 - 6100$ K, $\log g = 4 - 4.9$ and Kepler magnitude 10-15 mag). While Berger et al. (2018) also shows that subgiant contaminations in the Kepler catalogue is less severe than what was previously reported, we choose to add a further restriction by imposing that the value of Gaia-derived $R_\ast$ must lie between 0.4 and $2R_\odot$, to avoid including previously misclassified giants or subgiants to our Sun-like sample of stars.

From these boundaries on stellar properties we obtain a sample of 38437 stars similar to the Sun in the Kepler field for which new values of radii have been derived using Gaia DR2 parallaxes. In the left-hand panels of Fig. 1 we show a comparison of the distributions of the uncertainties on the stellar radii for this Sun-like sample as derived from the Kepler catalogue and from DR2 parallaxes, showing how the newly derived stellar radius are about 3 times more precise than the Kepler-derived ones. In the right-hand panels of Fig. 1 we also show a similar comparison for the radii of the 1827 candidates and confirmed planets orbiting these stars, this time showing an improvement on the radius precision.
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Figure 1. Upper panels: distributions of relative radii errors of the 177911 Sun-like sample and the 1827 candidates and confirmed planets they host studied in the present work, as derived from the Kepler catalogue. Lower panels: corresponding distributions as derived from Gaia DR2 parallaxes. The median value of each distribution is shown in each panel’s upper right corner.

of about 1.5 times. This result stresses again the importance of well-defined stellar radii in correctly characterizing the physical properties of the exoplanets orbiting them.

In the left panel of Fig. 2, we instead show the radius of the confirmed and candidate planets found in our sample versus their incident fluxes in Earth units, a black box showing our chosen boundaries for Earth-like planets; considering both the results of Fulton et al. (2017) and Fulton & Petigura (2018) on radii distribution for small planets and the habitable zone model of Kopparapu et al. (2013) and Kopparapu et al. (2014) with recent Venus and early Mars limits for inner and outer habitability boundaries respectively, we define an Earth-like planet as having radius between 1.0 and 1.75 $R_\oplus$ and incident flux between 0.2 and 2.0 $F_\oplus$, a definition that we note to be more restrictive than the one used in Petigura et al. (2013). While we find a total of 21 candidate and confirmed exoplanets in this habitability region, we choose to take into account both the uncertainties on radius and flux to further restrict our planetary sample. By drawing
Figure 2. Left panel: radii and incident fluxes for the 1827 candidate and confirmed planets orbiting the Sun-like sample, our Earth-like region \((R_p = 1 - 1.75 \, R_{\oplus}, \, F = 0.2 - 2 \, F_{\oplus})\) highlighted as a black box. Right panel: the neighborhood of the Earth-like region, candidates and confirmed planets shown as gray circles and stars respectively. Our final Earth-like candidate and confirmed planets sample are instead shown as black circles and stars.

Table 1. Planetary radii and incident fluxes in Earth units for the final sample of 3 confirmed and 13 candidates lying inside the selected Earth-like region.

|       | DR2 \(R_p (R_{\oplus})\) | Kepler \(R_p (R_{\oplus})\) | Flux \(F_{\oplus}\) |
|-------|--------------------------|-----------------------------|------------------|
| Kepler-442 b | 1.39^{+0.10}_{-0.10} | 1.34^{+0.11}_{-0.18} | 0.90^{+0.11}_{-0.11} |
| Kepler-62 f  | 1.54^{+0.09}_{-0.10} | 1.43^{+0.08}_{-0.10} | 0.47^{+0.06}_{-0.05} |
| Kepler-1544 b | 1.68^{+0.14}_{-0.10} | 1.69^{+0.10}_{-0.06} | 0.82^{+0.10}_{-0.09} |
| K08242.01   | 1.45^{+0.15}_{-0.22} | 1.36^{+0.32}_{-0.11} | 0.90^{+0.19}_{-0.18} |
| K05087.01   | 1.15^{+0.11}_{-0.14} | 1.55^{+0.59}_{-0.35} | 0.36^{+0.04}_{-0.04} |
| K07176.01   | 1.46^{+0.15}_{-0.25} | 1.27^{+0.25}_{-0.10} | 0.52^{+0.13}_{-0.12} |
| K07749.01   | 1.67^{+0.17}_{-0.12} | 1.89^{+0.12}_{-0.19} | 1.85^{+0.23}_{-0.21} |
| K03456.02   | 1.35^{+0.13}_{-0.13} | 1.18^{+0.44}_{-0.16} | 0.86^{+0.10}_{-0.09} |
| K05387.01   | 1.35^{+0.13}_{-0.15} | 1.17^{+0.69}_{-0.14} | 0.23^{+0.05}_{-0.04} |
| K06971.01   | 1.60^{+0.28}_{-0.32} | 2.01^{+0.08}_{-0.13} | 1.16^{+0.14}_{-0.13} |
| K07591.01   | 1.24^{+0.17}_{-0.10} | 1.30^{+0.18}_{-0.10} | 0.30^{+0.06}_{-0.06} |
| K05556.01   | 1.67^{+0.20}_{-0.20} | 1.86^{+0.69}_{-0.36} | 0.37^{+0.08}_{-0.07} |
| K07179.01   | 1.06^{+0.28}_{-0.14} | 1.18^{+0.49}_{-0.32} | 1.03^{+0.21}_{-0.21} |
| K07953.01   | 1.64^{+0.20}_{-0.12} | 1.43^{+0.33}_{-0.12} | 0.70^{+0.15}_{-0.15} |
| K05810.01   | 1.30^{+0.18}_{-0.20} | 2.25^{+1.20}_{-0.71} | 0.53^{+0.06}_{-0.06} |
| K05948.01   | 1.49^{+0.21}_{-0.21} | 1.23^{+0.55}_{-0.08} | 0.64^{+0.08}_{-0.07} |

for each planet 10^4 random values of planetary radius and incident flux within their respective error bars and selecting as proper Earth-like planets only those falling at least 60% of the times inside our boundaries of 1.0-1.75 \(R_{\oplus}\) and 0.2-2.0 \(F_{\oplus}\), we obtain 13 candidates and 3 confirmed planets falling inside our habitability region, shown in the right panel of Fig. 2 as black circles and stars respectively. The values of radii and fluxes for this final planetary sample are listed in Table 1.
3. Detection efficiency and Earth-like planets frequency

To finally obtain a revised assessment of the frequency of Earth-like planets $\eta_{\oplus}$ in the Kepler field, we must know the number of stars $N_*$ around which Kepler is sensitive enough to detect the transit of an Earth-sized planet in the circumstellar habitable zone so that we can calculate the occurrence rate as:

$$\eta_{\oplus} = \frac{1}{N_*} \sum_{i} \frac{a_i}{R_{*,i}}$$

being $a_i$ and $R_{*,i}$ the semimajor axis and host star radius of the detected Earth-like planets listed in Table 1 orbiting those stars for which Kepler is indeed sensitive to Earth-like transits.

To assess Kepler’s detection efficiency we follow the results and methods outlined in Christiansen et al. (2016) in which a single simulated planet with random orbital period between 0.5 and 500 d and radius between 0.25 and $7\,R_{\oplus}$ is injected around a sample of 159013 stars across the Kepler focal plane in order to assess the detection efficiency of the Kepler pipeline, considering as retrieved an injection having at least three transits with a Multiple Event Statistics (MES) value above the $7.1\sigma$ threshold and if the pipeline identifies the orbital period within 3% of its injected value. Christiansen et al. (2016) also provide a recipe for calculating the Kepler detection efficiency within a certain stellar and planetary parameter space, by selecting only the injections falling within one’s desired parameters and fitting the resulting ratio between injected signals $N_{inj}$ and retrieved signals $N_{det}$ with a 4-parameter logistics function in the form:

$$F(x; a, b, c, d) = d + \frac{a - d}{1 + \left( \frac{x}{c} \right)^b}$$

from which it is possible to calculate the detection efficiency as $F(x_{thr})$, being $x_{thr}$ the selected MES threshold for the type of signals for which the efficiency is calculated.

Following therefore the injections lying within our aforementioned range of stellar and planetary parameters, so to search for the detection efficiency of Earth-like transits around Sun-like stars, and following the advice in Christiansen et al. (2016) to select a high MES threshold ($\text{MES}>15$) for the $\sim$1 yr transits we are searching for, we find a total of 1041 stars with successfully retrieved injections and a detection efficiency of 77%, from which we finally obtain the number of stars in our sample around which Kepler is able to detect an Earth-like transit of $N_*=803$. Around these $N_*$ stars we find only the planets Kepler-1544 b and K07591.01 amongst our list of Earth-like known planets in the Kepler field, from which we can therefore compute values of Earth-like planets $\eta_{\oplus}$ of $20.88^{+25.74}_{-8.22}\%$ for the confirmed planets population and of $35.01^{+25.00}_{-15.66}\%$ for the candidate population.

The reason for finding only two of our 16 Earth-like planets amongst the $N_*$ stars for which Earth-like transits were successfully retrieved is due to the fact that in assessing Kepler’s detection efficiency through the injection of simulated planets the authors of the cited paper showed no particular interest in Earth-sized planets, injecting signals between 0.25 and $7\,R_{\oplus}$ not necessarily corresponding to the known planets found around the stellar sample. For example, the signal injected around the star Kepler-442 corresponds to a $1.98\,R_{\oplus}$ planets orbiting at 423 days, too big in size and too distant from the star to be considered Earth-like according to our definitions and certainly not accurately representing the detected $R_p=1.39\,R_{\oplus}$ and $P=423$ d of Kepler-442 b which instead falls into our definition of Earth-like planet. To account for this bias, we can extrapolate our results of $\eta_{\oplus}$ to the 6872 Sun-like stars in our sample...
having stellar characteristics similar to the 803 stars for which Christiansen et al. (2016) injected and retrieved Earth-like transits, assuming that for similar stars the same type of transit would be similarly detectable. Selecting therefore the stars in our sample having characteristics more similar to the Sun and to those with successful retrievals (namely $R_* = 0.6 - 1 \ R_\odot$, $\log g = 4.5 - 4.7$ and Kepler magnitude between 13.5 and 15 mag) and assuming a similar detection efficiency of 77% we obtain an extended sample of $N_\ast = 6872$ Sun-like stars, for which using a typically Earth-like value of $a_i/R_{\ast,i} \sim 215$ we then obtain $\eta_\oplus = 26.77^{+9.92}_{-6.27} \%$.

Finally, we can also consider the $\sim 10\%$ false positive rate for Kepler candidate planets below 2 Earth radii reported by Fressin et al. (2013), Désert et al. (2015) in order to accordingly correct the number of Earth-like candidates found, obtaining from this an estimate of frequency of $\eta_\oplus = 24.10^{+8.92}_{-5.88} \%$.

4. Conclusions

While the astrometric signal produced by an Earth-like ($R_p = 1 - 1.75 \ R_\oplus$, $F = 0.2 - 2 \ F_\oplus$) on its host star is beyond the expected end-of-mission accuracy of Gaia, the accurate parallax measurements provided by the satellite is an important factor in deriving more precise estimates of stellar radius and, in conjunction with crossmatching with other planet-finding missions such as Kepler, can and will be instrumental in furthering our understanding of the populations and occurrence rates of extrasolar planets.

Starting from the crossmatching between Gaia DR2 and Kepler detailed in Berger et al. (2018) and following the assessment of Kepler detection efficiency provided in Christiansen et al. (2016) we have obtained an updated estimate of the frequency $\eta_\oplus$ of Earth-like planets orbiting Sun-like stars of $20.88^{+25.74}_{-18.22} \%$ considering the confirmed Earth-like planet population and of $35.01^{+25.00}_{-15.66} \%$ for the candidate population. We have also extrapolated this results to a larger sample of Solar-type stars for which Kepler would have been sensitive to a Earth-like transit, obtaining instead $\eta_\oplus = 26.77^{+9.92}_{-6.27} \%$. Finally, by correcting the sample for the Kepler false positive rate of $\sim 10\%$ for $R_p < 2 \ R_\oplus$ we find a frequency of $\eta_\oplus = 24.10^{+8.92}_{-5.88} \%$.

All these values are generally in agreement with the $22\pm8\%$ derived in Petigura et al. (2013) which however used a more generous definition of Earth-like planet ($R_p = 1.0 - 2.0 \ R_\oplus$ and $F = 0.25 - 4 \ F_\oplus$). By finding similar frequencies having instead used more restrictive boundaries, we argue that this may be taken as a hint that the number of Earth-like planets in the Milky Way is higher than anticipated by the literature. This tantalizing possibility provides a high potential for any current or future planet-hunting experiments specifically designed to search for potentially habitable Earths orbiting solar-type stars, such as the spectrograph ESPRESSO (Pepe et al. (2014)), the space observatory PLATO (Rauer et al. (2014)) and the proposed ESA astrometry satellite Theia (Theia Collaboration (2017)). In particular, Theia is expected to detect and characterize any super Earths with $M_p < 2.2 \ M_\oplus$ orbiting around 60 of the stars nearest to the Sun, showing again how astrometry promises to further push the boundaries of exoplanetology.

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References

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Discussion

DAVID BENNETT: Is your analysis equivalent to adjusting the radii for all the stars and planets in the Christiansen et al. analysis to the new Gaia radii?

DOMENICO BARBATO: Yes, because Christiansen’s injected signals are not actually related to any existing planets found around the sample stars and are merely simulated planets randomized to assess the detection efficiency of the Kepler pipeline. Also, the radii of solar-type stars show little variation between Kepler and DR2 nominal values, averaging at about 0.3 solar radii, and therefore Christiansen’s analysis on transit depth should not suffer from significant variations.