Discovery of the first Earth-sized planets orbiting a star other than our Sun in the Kepler-20 system

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Abstract

Discovering other worlds the size of our own has been a long-held dream of astronomers. The transiting planets Kepler-20\textsuperscript{e} and Kepler-20\textsuperscript{f}, which belong to a multi-planet system, hold a very special place among the many groundbreaking discoveries of the Kepler mission because they finally realized that dream. The radius of Kepler-20\textsuperscript{f} is essentially identical to that of the Earth, while Kepler-20\textsuperscript{e} is even smaller (0.87 \( R_\oplus \)), and was the first exoplanet to earn that distinction. Their masses, however, are too light to measure with current instrumentation, and this has prevented their confirmation by the usual Doppler technique that has been used so successfully to confirm many other larger planets. To persuade themselves of the planetary nature of these tiny objects, astronomers employed instead a statistical technique to “validate” them, showing that the likelihood they are planets is orders of magnitude larger than a false positive. Kepler-20\textsuperscript{e} and 20\textsuperscript{f} orbit their Sun-like star every 6.1 and 19.6 days, respectively, and are most likely of rocky composition. Here we review the history of how they were found, and present an overview of the methodology that was used to validate them.

Keywords: Kepler mission, transiting planets, false positives, multi-planet systems, Kepler-20, statistical validation.

1. Introduction

Thanks to the Kepler mission we now know that small planets similar in size to the Earth are common throughout the Galaxy (Howard et al., 2012; Fressin et al., 2013; Dressing \\& Charbonneau, 2013, 2015; Petigura et al., 2013; Marcy et al., 2014; Burke et al., 2015). What seems so clear now was
not at all obvious at the time the spacecraft was launched in March of 2009, as no such planets had been found outside the solar system. The ones discovered until then by the transit method were all Neptune-size ($\sim 4 R_\oplus$) or larger. These had all been confirmed by measuring their dynamical masses through high precision radial-velocity observations, to show that they are indeed in the planetary range. Here we recount the developments that led to the discovery of the first two Earth-sized exoplanets, Kepler-20 e and Kepler-20 f (Fressin et al., 2012), which marked a very important milestone in the field of exoplanet research. Unlike their larger cousins that are amenable to Doppler studies, the masses of Kepler-20 e and Kepler-20 f have not been measured because the reflex motion they induce on the host star is too small to detect. For this reason these objects required the use of an entirely different analysis technique to assess their planetary nature.

The importance of careful vetting of candidates and of confirmation by the Doppler technique became painfully obvious as soon as ground-based transit surveys began reporting planetary candidates. It was quickly found that the vast majority turned out to be false positives of one kind or another (see, e.g., Brown, 2003), with estimates of the false positive rates reaching as high as 90% or 95% in some cases (Konacki et al., 2003; O’Donovan et al., 2006a; Latham, 2007). The most common types of astrophysical false positives, often referred to as “blends”, are eclipsing binaries that happen to be along the line of sight, whether physically associated with the target or not. When this happens, the otherwise deep eclipses of the binary are greatly attenuated by the target star and made to look so small that they can be indistinguishable from the transit signals of true planets. As it turns out, however, confirming a planet by measuring the reflex motion of the parent star is not always feasible. For example, the star may be too faint, it may be rotating too rapidly, or it may be too chromospherically active to allow the necessary precision in the radial velocities. Or even if it does lend itself to Doppler studies, the signal may simply be too small to detect, if the orbital period is long and/or the planetary mass too small relative to the mass of the star.

This was precisely the case for Kepler-20 e and Kepler-20 f. As their des-

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1The era of smaller planet discoveries began in earnest later that same year with the CoRoT mission (Rouan et al., 1998; Baglin et al., 2006), and the announcement of the planet CoRoT-7 b (Léger et al., 2009; Queloz et al., 2009), an object about 1.7 times larger than the Earth.
ignations suggest, these were the fourth and fifth transit-like signals detected in the photometric observations of Kepler-20 (KIC 6850504), a V = 12.5, mid G-type star in the constellation Lyra (Gautier et al., 2012), and one of the many multi-planet systems ("multis") that Kepler would find. For a review of the discovery and implications of multis, we refer the reader to the article by Steffen & Lissauer (2019) in this Special Issue. With transit depths each under 100 parts per million hinting at objects of both small sizes and small masses, the absence of corresponding radial-velocity signatures was not all that surprising. As an alternative to dynamical confirmation, an attempt was made by Gautier et al. (2012) to "validate" these two signals in a statistical way using a procedure that had become known as BLENDER. The idea behind BLENDER is to simulate blend configurations all the way through to the light curves they are expected to produce, and to use the shape of the real transits to discriminate against as many of those blends as possible. Other blends may be rejected if additional observations indicate the intruding objects would have been uncovered. The technique then aims to show in a quantitative way that the likelihood of the remaining false positives is much smaller than that of a true planet. This approach had been used in a few other cases before, but it was relatively new at the time and was not sufficient to demonstrate the planetary nature of Kepler-20 e and 20 f to a high enough degree of confidence. Further improvements to BLENDER would be required, as we describe below, and the procedure did eventually succeed in showing beyond a reasonable doubt that the two objects are indeed Earth-sized or smaller planets, with radii of \( R_p = 0.87 R_\oplus \) and 1.03 \( R_\oplus \), respectively, as measured initially by Pressin et al. (2012).

The development of the validation methodology represents a significant advance in our ability to discover small transiting planets. So far it is the only alternative we have when the mass cannot be measured directly, either by the Doppler effect or by modeling transit timing variations (TTVs) in multi-planet systems. In fact, statistical validation is now the approach that has verified the largest number of transiting planets from Kepler and its successor mission K2, and promises to be invaluable for future space-based transit searches as well. Because of its considerable impact for small planets discoveries, and in the spirit of this special issue, we chronicle in the next section the history of how validation came about, leading up to its application to Kepler-20 e and 20 f. The more technical details of the method may be found in the sources cited below.
2. Statistical validation: a pathway to the discovery of small planets

Readers familiar with the early history of photometric searches for transiting planets may recall that the very first lists of candidates, following the momentous discovery of HD 209458 b (Charbonneau et al., 2000; Henry et al., 2000), were released by the Optical Gravitational Lensing Experiment (OGLE; Udalski et al., 2002a,b). Out of one of those lists emerged the second known transiting planet, OGLE-TR-56 b (Konacki et al., 2003), a Jovian-size, Jovian-mass object with an orbital period of just 1.2 days that was also the first to be discovered in a photometric survey. Although it was confirmed dynamically, the mass determination for OGLE-TR-56 b was based on few and very challenging radial-velocity observations given the faintness of the host star \((V = 16.6)\), and extra precaution was taken to examine possible false positive scenarios, particularly since the target is projected against the crowded field of the Galactic center.

It is in this context that one of us (G.T.) developed numerical procedures to simulate realistic light curves resulting from a blend with an eclipsing binary along the line of sight. A wide range of false positive scenarios were generated and compared against the OGLE photometry, assuming different binary properties and also varying the relative distance between the binary and the target. These tests revealed that many of the configurations resulted in light curves that fit the real observations just as well as a planetary transit model, matching both the depth and the overall shape of the transits. However, it was also found that for all of these blends the predicted brightness of the eclipsing binary together with the radial-velocity semi-amplitude of its primary component would be expected to cause noticeable asymmetries in the spectral line profiles, or even the presence of a second set of lines moving around with the 1.2-day period of the signal, and yet neither of these was seen. This provided further support for the planetary nature of the object. The mathematical details of the technique were laid out by Torres et al. (2004), along with an application to another candidate that did turn out to be a false positive (OGLE-TR-33).

The capability was later added to generate blend light curves simultaneously in other passbands, and to predict the overall colors of the blend.

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2HD 209458 b, the first known transiting exoplanet, was originally found in a radial-velocity survey and only later discovered to undergo transits.
both of which can supply further useful checks against follow-up observations that might be available. Simulations like these, coupled with an analysis of the spectral line bisectors (e.g., Torres et al., 2005), were used also by other ground-based transit surveys as additional insurance against blends (Mandushev et al., 2005; O’Donovan et al., 2006a,b; Bakos et al., 2007). However, in cases where planets were confirmed in these surveys, it was always a mass measurement via radial velocities that provided the final proof, and the blend simulations played only a supporting role.

2.1. First application to small planets: Kepler-9 d

When the Kepler mission began finding very small transit-like signals that could not be confirmed dynamically, it became clear that the simulation approach would come to be crucial. A way was needed not only to improve the ability to reject false positives as much as possible, but more importantly, to quantify the probability that any one of the remaining blends might actually be causing the small drops in brightness. The first real test came with Kepler-9 d (Torres et al., 2011), a super-Earth with a size of about 1.6$R_\oplus$. This was the third signal found in the multi-planet system Kepler-9 (Holman et al., 2010) featuring two larger Saturn-sized objects ($\sim 9 R_\oplus$), which were also the first to display unambiguous TTVs (see the review article by Ragozzine & Holman, 2019, this Special Issue).

The simulations for Kepler-9 d were expanded to include a more complete, grid-based exploration of parameter space for false positives. In addition to eclipsing binaries, the numerical experiments now included scenarios involving an intruding single star located anywhere along the line of sight that is transited by a larger planet, rather than by another star. While it may be argued that this type of contaminant is in itself a bona fide planetary system, the unfortunate alignment with the star one is interested in causes the transits to appear shallower, simulating the presence of a smaller planet orbiting the target star. As the goal was to prove the existence of a planet of small size around the target (rather than a larger one of unknown size around the companion), these configurations were considered as false positives. Allowance was made also for eccentric orbits for all categories of simulated blends, and for differential interstellar extinction between the intruding star or binary and the target. Additionally, a more thorough use was made of available follow-up observations to help rule out blends. Detection limits from high-resolution imaging were now taken into account, as well as limits on unseen spectroscopic companions in high-resolution spectra, measured color indices
for the target, and other limits on nearby companions based on an analysis of the flux centroids from the *Kepler* images themselves. All of these helped, but many false positive scenarios still remained viable.

The expected numbers of viable false positives of different kinds is of course a function of the number density of stars at the sky location of the target, and depends also on how common eclipsing binaries and larger planets are. For *Kepler-9* d these blend frequencies were calculated in discrete magnitude bins by counting up the ones that were permitted by all observational constraints, using number densities from Galactic structure models along with estimates of the rates of occurrence of eclipsing binaries and larger planets from the early *Kepler* results. It was also realized that in order to obtain a proper false alarm probability (FAP), or equivalently a confidence level that the signal is due to a true super-Earth-sized planet, an estimate was required of the rate of occurrence of such planets. Expressed in terms of the numbers of expected false positives and planets, \( \text{FAP} = \frac{N_{FP}}{N_{FP} + N_p} \). However, the planet occurrence rate (referred to as the “planet prior”) was not well known at the time, so arguments were made drawing on statistics from Doppler surveys, on theoretical considerations, and on preliminary *Kepler* results that were based on candidate detections rather than confirmed planets. The most conservative of those estimates allowed *Kepler-9* d to be validated to a sufficiently high level of confidence corresponding to a false alarm probability of \( 6 \times 10^{-4} \) (Torres et al., 2011).

This framework for simulating blend scenarios and performing statistical validation became known as BLENDER, and over the next year or so it was applied in a few other cases with relatively minor changes. The software to perform the computationally intensive blend simulations and map out parameter space was ported to the Pleiades supercomputer at the NASA Ames Research Center (California, USA), with the help of Chris Henze.

### 2.2. The challenge of even smaller planets

*Kepler-20* e and 20 f were more demanding still than *Kepler-9* d because of the shallower transits and the associated smaller signal-to-noise ratios. This meant they contain less information with which to constrain the detailed shape of the transit and rule out blends. The simple-minded procedure of tabulating blends in discrete magnitude bins to compute their frequencies was replaced by a more sophisticated Monte Carlo approach. Background stars were drawn at random from a Galactic structure model, and were assigned
either a stellar or a planetary companion, depending on the type of false positive. This was done taking into account the known properties of eclipsing binaries and the size distribution of larger planet candidates, as determined from the Kepler mission itself. For blends consisting of a planet transiting another star physically associated with the target (hierarchical triple configuration) the simulations placed such companions in randomly oriented orbits around the host star following the known distributions of periods, mass ratios, and eccentricities of binary systems. The frequencies for each type of false positive were then calculated after removing configurations inconsistent with constraints from the lightcurve morphology and the follow-up observations. The outcome of this exercise for Kepler-20 e gave a blend frequency of background eclipsing binaries of $3.1 \times 10^{-8}$, a frequency of background stars transited by larger planets of $2.1 \times 10^{-7}$, and a frequency of hierarchical triple configurations of $5.0 \times 10^{-7}$. These three contributions added up to a total blend frequency of $7.4 \times 10^{-7}$. For Kepler-20 f the numbers were $1.2 \times 10^{-6} + 4.5 \times 10^{-7} + 3.6 \times 10^{-6} \approx 5.2 \times 10^{-6}$. The planet priors, i.e., the a priori chance that the parent star Kepler-20 has a planet of a similar size as implied by each of the two signals, were estimated again using the catalog of Kepler objects of interest (KOIs), which had expanded by then. As KOIs are still only candidates, the conservative assumption was made that only 10% of them are real planets, even though other estimates at the time were nearly an order of magnitude larger (e.g., Morton & Johnson, 2011). The resulting planet priors were $3.1 \times 10^{-4}$ for Kepler-20 e and $7.5 \times 10^{-4}$ for Kepler-20 f.

By this time it had already been shown that multi-planet systems such as Kepler-20 tend to be coplanar (Lissauer et al., 2011). Because Kepler-20 was already known to have three other transiting planets (Kepler-20 b, 20 c, and 20 d; see below), this made it much more likely that Kepler-20 has a transiting planet at the periods of Kepler-20 e and 20 f than a random Kepler target. With this “multiplicity boost”, the planet priors for 20 d and 20 f increased to $2.5 \times 10^{-3}$ and $7.1 \times 10^{-3}$, respectively. Comparing these to the total blend frequencies from above, the false alarm rates became $3.0 \times 10^{-4}$ for Kepler-20 e and $7.3 \times 10^{-4}$ for Kepler-20 f, which were deemed sufficiently small to declare the candidates validated as true Earth-sized planets.

Beyond the success in demonstrating the planetary nature of the first two known Earth-sized planets, statistical validation using BLENDER has been applied to many other planets, including some of the most iconic discoveries of the Kepler mission. Examples include Kepler’s first rocky planet (Kepler-10 b; Batalha et al., 2011), the first small planets in the habitable
zone of their parent stars (Kepler-22 b, Borucki et al. 2012, and Kepler-62 f, Borucki et al. 2013; see also the article by Borucki et al. 2019 in this Special Issue), the first two transiting planets ever discovered in a cluster (Kepler-66 b and Kepler-67 b; Meibom et al. 2013), the discovery of a sub-Mercury-sized planet (Kepler-37 b; Barclay et al. 2013), a transiting planet near the snow line of its parent star (Kepler-421 b; Kipping et al. 2014), a super-Earth in the habitable zone of a G2 star with an orbital period near one year (385 days, Kepler-452 b; Jenkins et al. 2015), the discovery of a sub-Neptune-sized planet in the open cluster Ruprecht 147 (K2-231 b; Curtis et al. 2018), and others.

Statistical validation as an exoplanet discovery tool when Doppler confirmation is not feasible is now mainstream, and while BLENDER led the way, several other versions of the same approach with different strengths have now been implemented that were inspired by BLENDER, such as vespa (Morton, 2012) and PASTIS (Díaz et al., 2014). These methods all work by comparing priors from various scenarios (true planets and false positives) to arrive at a confidence level for planethood. A different technique to validate candidates in multi-planet systems was developed by Lissauer et al. (2012), and refined by Lissauer et al. (2014), which is based on planet multiplicity statistics. With reasonable assumptions on the nature and distribution of false positives, these authors showed that almost all multi-planet candidates are true planets rather than false positives, and that the higher the multiplicity, the more likely the candidates are real planets. This immediately allowed the validation in bulk of hundreds of Kepler planets in multis.

Interestingly, of the several thousand exoplanets now known, the vast majority were actually validated (most with vespa, or based on multiplicity statistics when in multis) rather than confirmed dynamically (see, e.g., Rowe et al. 2014; Morton et al. 2016; Crossfield et al. 2016; Mayo et al. 2018). This is partly a reflection of the fact that small planets with undetectable Doppler signals far outnumber larger ones, that many of the Kepler host stars are faint and unsuitable for Doppler studies, and that observing facilities capable of high-precision (m s\(^{-1}\)) radial-velocity measurements are still very few and far between.

3. Kepler-20 e and Kepler-20 f: two planets the size of the Earth

The discovery of the Kepler-20 multi-planet system was announced to the community by Gautier et al. (2012). It featured three transiting planets
(20 b, 20 c, 20 d) with orbital periods ranging from 3.7 to 78 days that were confirmed in the traditional way, and that have sizes estimated by those authors of 1.9, 3.1, and 2.8 \( R_\oplus \). The detections were based on eight quarters of *Kepler* long-cadence (30 min) observations made between 2009 May and 2011 March. The same paper gave news of the detection of two additional transit-like signals in the same star that were much shallower and had periods of 6.1 and 19.6 days, respectively, but they were left unconfirmed, as mentioned earlier. The validation of these two signals as Kepler-20 e and 20 f, the first two Earth-sized planets, was left to Fressin et al. (2012). The planetary sizes reported by these authors, based on a determination of the properties of the host star and fits to the light curves, were \( 0.868^{+0.074}_{-0.096} R_\oplus \) and \( 1.03^{+0.10}_{-0.13} R_\oplus \), respectively. Fressin et al. (2012) noted also that the first of these planets, Kepler-20 e, is potentially smaller than Venus. Until then the smallest known exoplanet around a Sun-like star had been Kepler-10 b, with a measured radius of \( 1.42 R_\oplus \) (Batalha et al., 2011). While the difference may not seem all that significant, the validation of Kepler-20 e and 20 f was seen by many as crossing a threshold of sorts, advancing the frontier of discovery into the realm of planets the size of our own, and smaller.

The Kepler-20 multi-planet system has received additional attention more recently. Buchhave et al. (2016) reported new radial-velocity measurements, and revisited both the stellar parameter determination and the photometric solutions, now using the full complement of short-cadence (1 min) observations of the star obtained in Quarters 3 through 17, rather than the smaller number of long-cadence data used previously. This is important because the very brief ingress and egress phases of the transit that are so critical for constraining the planetary sizes are much better resolved with the 1 min integrations than the 30 min integrations. The new stellar properties also benefited from asteroseismic constraints the authors were able to extract from the short-cadence observations.

The updated properties obtained by Buchhave et al. (2016) for Kepler-20 e and 20 f are listed in Table I. They include the orbital semimajor axes and the equilibrium temperatures, on the assumption of full energy redistribution and a Bond albedo of 0.3. The orbits were assumed to be circular. The planetary sizes are considerably better determined than before, although the actual values differ little from those of Fressin et al. (2012). This is the result of a trade-off in the recent work between a small increase in the stellar radius and a small reduction in the radius ratios \( R_p/R_\star \). Further improvements in the stellar properties of Kepler-20 are now possible thanks to the availability
Table 1: Main properties of Kepler-20 e and 20 f (Buchhave et al., 2016)

| Parameter | Kepler-20 e | Kepler-20 f |
|-----------|-------------|-------------|
| \(P\) (days) | \(6.098523^{+0.000006}_{-0.000014}\) | \(19.57758^{+0.000012}_{-0.000011}\) |
| \(T_c^*\) | \(968.9315^{+0.0022}_{-0.0007}\) | \(968.2071^{+0.0061}_{-0.0043}\) |
| \(R_p\) (\(R_\odot\)) | \(0.865^{+0.026}_{-0.028}\) | \(1.003^{+0.050}_{-0.089}\) |
| \(i\) (deg) | \(87.6^{+1.1}_{-0.1}\) | \(88.79^{+0.43}_{-0.07}\) |
| \(a\) (au) | \(0.0639^{+0.0019}_{-0.0014}\) | \(0.1396^{+0.0036}_{-0.0035}\) |
| \(T_{eq}\) (K)** | \(1040 \pm 22\) | \(705 \pm 16\) |

* Time of mid transit expressed as BJD−2,454,000.
** Equilibrium temperatures taken from Fressin et al. (2012).

of a precise parallax from the second data release (DR2) of the Gaia catalog (Gaia Collaboration et al., 2018), which places the star at a distance of \(282.5 \pm 1.7\) pc. Using that measurement and a different methodology, Berger et al. (2018) have reported a stellar radius of \(R_* = 0.887^{+0.037}_{-0.036} R_\odot\), which is about 8% smaller than the determination by Buchhave et al. (2016) of \(0.964 \pm 0.018 R_\odot\) (a 1.9\(\sigma\) difference). The new value would reduce the sizes of Kepler-20 e and 20 f even further to about 0.80 and 0.92 \(R_\oplus\), respectively, making them both nominally smaller than the Earth, though with uncertainties increased by a factor of two.

4. Kepler-20 architecture, formation, and planetary composition

With their new radial-velocity measurements Buchhave et al. (2016) were able to improve the mass determinations for the three larger planets Kepler-20 b, 20 c, and 20 d, but the two smaller ones remain below the detection threshold. Even assuming a rocky composition, which would maximize their radial-velocity signal, they are expected to induce reflex motions on the star with semi-amplitudes of only \(\sim 20\) cm s\(^{-1}\). Interestingly, however, the new Doppler measurements have revealed a sixth planet (Kepler-20 g) in this already extraordinary system, which does not undergo transits. It is nestled between the outer two previously known planets 20 f (\(P = 19.6\) days) and 20 d (\(P = 77.6\) days), and revolves around the star once every 34.9 days. Buchhave et al. (2016) report it to be more massive than any of the others, with a minimum mass of \(M_p \sin i = 20.0^{+3.1}_{-3.6} M_\oplus\), which is larger than that
of Neptune. For completeness, we summarize in Table 2 the main properties of this new planet and the remaining ones in the system. We include the measured velocity semi-amplitudes, $K$, the estimated orbital eccentricities, the planetary masses, and the mean densities, $\rho_p$. A schematic view of the architecture of the Kepler-20 system is shown in Figure 1.

Kepler-20 is quite remarkable in that it is very compact: its six known planets, five of which transit, are all packed within the orbital distance of Mercury in our own solar system. Compactness has now been found to be a feature of many other multi-planet systems as well. Furthermore, Gautier et al. (2012) pointed out a striking feature of Kepler-20 that is the presence of small and likely rocky Earth-size planets (20 e and 20 f) interspersed between larger sub-Neptune planets at smaller and larger orbital semimajor axes. This is quite different from our own solar system, in which the terrestrial planets, gas giants, and ice giants are neatly segregated in regions with increasing distance from the Sun. Recent studies of samples of multi-planet systems have found that the patterns in planet sizes, masses, and spacing are linked through formation and subsequent orbital dynamics, although the full complexity of planetary system architectures is not yet well understood (see, e.g., Millholland et al., 2017; Weiss et al., 2018).

The long-term stability of the Kepler-20 system was investigated numer-

| Parameter | Kepler-20 b | Kepler-20 c | Kepler-20 g | Kepler-20 d |
|-----------|-------------|-------------|-------------|-------------|
| $P$ (days) | 3.696       | 10.854      | 34.940      | 77.611      |
| $T_c$*    | 967.50201   | 971.60796   | 967.50027   | 997.7303    |
| $R_p$ ($R_\oplus$) | 1.868 | 3.047 | ... | 2.744 |
| $i$ (deg) | 87.4        | 89.8        | < 88.7**    | 89.7        |
| $a$ (au)  | 0.0463      | 0.0949      | 0.2055      | 0.3506      |
| $e$       | 0.03        | 0.16        | 0.15        | ...         |
| $K$ (m s$^{-1}$) | 4.20 | 3.84 | 4.10 | 1.57 |
| $M_p$ ($M_\oplus$)** | 9.7   | 12.8      | 20.0        | 10.1        |
| $\rho_p$ (g cm$^{-3}$) | 8.2  | 2.5       | ...         | 2.7         |
| $T_{eq}$ (K) | 1105 | 772       | 524         | 401         |

* Time of mid transit expressed as BJD−2,454,000.
** Upper bound on inclination inferred here from the lack of transits.
***For Kepler-20 g this is the minimum mass $M_p \sin i$. 

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Figure 1: The Kepler-20 system: Orbital configuration of the Kepler-20 system, reproduced from Figure 1 of Buchhave et al. (2016). All six planets are contained within the orbital distance of Mercury in our Solar System. Orbital distances are drawn to scale, and planet sizes are rendered in correct proportion to each other, though not on the same scale as the orbits. The size of Kepler-20g was estimated using its mass and assuming a composition similar to Kepler-20c. Orbits drawn in blue represent planets with mass measurements.

ically by Gautier et al. (2012) prior to the discovery of the massive non-transiting planet Kepler-20g, and by Buchhave et al. (2016) afterward. Both studies assumed masses for Kepler-20e and 20f of about 0.65 and 1.0 $M_\oplus$, respectively, and neither found any indication of instability over a 10 million year period, provided the eccentricities (which are still poorly determined) are small. Buchhave et al. (2016) concluded that the Kepler-20 system is consistent with being dynamically cold, with relatively small eccentricities and inclination angles, and that it may have formed during the transition phase when the circumstellar disk has a high solid surface density but a low or moderate gas surface density, according to theoretical modeling by Lee & Chiang (2016).
Kepler-20 e and 20 f are so small that they most likely have a rocky composition like the Earth. Based on the properties of the parent star and the orbital semimajor axes of these two bodies, we estimate they now receive, respectively, about 187 and 39 times the incident radiation that the Earth receives from the Sun. Any primordial gaseous envelopes would have been completely lost to atmospheric photoevaporation (e.g., López et al., 2012) or perhaps other processes such as impact erosion (e.g., Inamdar & Schlichting, 2015).

Thanks to the improved mass determinations by Buchhave et al. (2016) for the other transiting planets in the system, their nature is now also coming into better focus. Despite the large radius of Kepler-20 b, the innermost planet, interior structure models by Zeng & Sasselov (2013) indicate it has a rocky composition that is consistent with an iron-to-silicate ratio similar to that of the Earth. We are likely seeing the bare core of a planet that lost its primordial atmosphere due to strong irradiation from the star, equivalent to more than 350 times the flux of the Sun impinging on the Earth. The masses and radii of Kepler-20 c and 20 d, on the other hand, lead to densities that indicate the presence of volatiles and/or a hydrogen/helium envelope.

5. Final words

Kepler-20 e and 20 f marked the first time astronomers were able to verify the presence of another world the size of our own around a Sun-like star. Since then, efforts have continued to push toward ever smaller planets, not only from space but also from the ground. As of this writing there are some 150 transiting planets known that are about the size of the Earth or smaller, all but a handful being *Kepler* discoveries. The exceptions are some of the planets in the fascinating multi-planet system TRAPPIST-1 (Gillon et al., 2017), detected recently from the ground around a nearby late-type M dwarf, and observed also by *K2* as well as *Spitzer*. The record-holder in terms of the smallest measured size is still Kepler-37 b (Barclay et al., 2013), a body that is smaller than the planet Mercury in our solar system.

In this growing collection of small planets only a few that reside in multi-planet systems have been confirmed dynamically, not by the Doppler technique but by taking advantage of their TTVs to measure their masses.

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3 Count based on the tabulation at [http://exoplanets.org/table](http://exoplanets.org/table), consulted on November 15, 2018.
An example is the TTV measurement of the mass of the Mars-sized planet Kepler-138 b by Jontof-Hutter et al. (2015). The rest have all been validated statistically. The use of the validation approach that has been so successful is likely to continue into the future in support of missions such as the Transiting Exoplanet Survey Satellite (TESS; Ricker et al., 2015), which has now begun to scrutinize the sky looking for small planets like Kepler-20 e and 20 f around bright nearby stars.

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