Below One Earth:
The Detection, Formation, and Properties of Subterrestrial Worlds

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Abstract The Solar System includes two planets — Mercury and Mars — significantly less massive than Earth, and all evidence indicates that planets of similar size orbit many stars. In fact, one of the first exoplanets to be discovered is a lunar-mass planet around a millisecond pulsar. Novel classes of exoplanets have inspired new ideas about planet formation and evolution, and these “sub-Earths” should be no exception: they include planets with masses between Mars and Venus for which there are no Solar System analogs. Advances in astronomical instrumentation and recent space missions have opened the sub-Earth frontier for exploration: the Kepler mission has discovered dozens of confirmed or candidate sub-Earths transiting their host stars. It can detect Mars-size planets around its smallest stellar targets, as well as exomoons of comparable size. Although the application of the Doppler method is currently limited by instrument stability, future spectrographs may detect equivalent planets orbiting close to nearby bright stars. Future space-based microlensing missions should be able to probe the sub-Earth population on much wider orbits. A census of sub-Earths will complete the reconnaissance of the exoplanet mass spectrum and test predictions of planet formation models, including whether low-mass M dwarf stars preferentially host the smallest planets. The properties of sub-Earths may reflect their low gravity, diverse origins, and environment, but they will be elusive: Observations of eclipsing systems by the James Webb Space Telescope may give us our first clues to the properties of these small worlds.

Keywords Exoplanets, Kepler mission, planet formation, astrobiology

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1 Uncovering the Sub-Earth Realm

The detection of Earth-size planets around other stars has long been a goal of astronomy. The Kepler space mission has discovered many such candidates (Borucki et al. 2011; Batalha et al. 2012), some of which are confirmed, and seeks to determine the fraction of solar-type stars that harbor Earth-size planets in their habitable zones (Borucki et al. 2010). While it is human nature to search for analogs of our home planet, the distribution of objects in our Solar System extends well below one Earth mass, i.e. Mars, Mercury, the “dwarf planets” Pluto and Ceres, and large planetary satellites such as Titan and Ganymede. However, the sub-Earth realm remains largely unexplored around other stars due to the limits of present detection methods. Like Mars, Europa and Titan, sub-Earth-mass objects in other planetary systems may prove to be of astrobiological interest.

For the purposes of this paper, we define sub-Earths or subterrestrial exoplanets (hereafter STEPs) as planets with radius \( R_p < 0.95 R_\oplus \). For a rocky planet this corresponds to a mass \( M_p < 0.82 M_\oplus \). Under this definition, a Venus twin \( (0.95 R_\oplus, 0.82 M_\oplus) \) is not a STEP, while analogs to Mercury \( (0.38 R_\oplus, 0.055 M_\oplus) \) and Mars \( (0.53 R_\oplus, 0.11 M_\oplus) \) are. Throughout this paper, we will refer to mass and radius interchangeably. Conceivably, planets might exist that have a radius smaller than 0.95 but a mass exceeding that of Earth (e.g. an “iron planet”), but we assume a single mass-radius relation appropriate for an Earth-like composition (i.e., Valencia et al. 2007, see 4.3 for more on expected STEP properties).

One of the first exoplanets discovered was the 0.02 \( M_\oplus \) pulsar planet PSR B1257+12A (Wolszczan 1994), however the Kepler mission is the primary source of STEP discoveries: As of April 2013, Kepler has discovered 7 STEPs and 36 candidates. Table 1 lists the parameters of all reported candidate and confirmed STEPs. Figure 1 plots the planets’ radii \( R_p \) and orbital periods \( P \). We include all confirmed and candidate planets with \( R_p + \sigma_{R_p} < 1 R_\oplus \), where \( \sigma_{R_p} \) is the uncertainty in radius.

STEPs may be very abundant. The distribution of planets rises steeply with both decreasing mass and decreasing radius down to 3 \( R_\oplus \) (Howard et al. 2010, 2012) but appears to be flat from 3 \( R_\oplus \) to 1 \( R_\oplus \), the completeness limit of Kepler (Fressin et al. 2013). A data pipeline sensitive to planets as small as 0.5 \( R_\oplus \) suggests that the Kepler planet size distribution for \( P = 5.0-10.8 \) days either remains flat or increases below 1 \( R_\oplus \) (Petigura et al. 2013). Although the detection rate in this region of parameter space is <50%, these findings indicate that STEPs are relatively common.

STEPs occupy diverse environments. Three STEPs orbit the M dwarf Kepler-42 (Muirhead et al. 2012a). Kepler-20e is part of a five-planet system that includes three gas giants and an Earth-size planet (Fressin et al. 2012). Contrary to the configuration of the Solar System, the two smallest planets of Kepler-20 orbit amongst the giants. KOIs 55.01 and 55.02 orbit within 0.008 AU of a B subdwarf and have day side temperatures exceeding 8000 K, allowing Kepler to detect their thermal emission at visible wavelengths (Charpinet et al. 2011). They somehow survived or avoided engulfment by the star during its red giant phase. An object transiting Kepler star KIC 12557548 every 15.7 hr is thought to be a disintegrating Mercury-size planet surrounded by a cloud of dust (Rappaport et al. 2012).

STEPs are part of the complete picture of planet formation and evolution. Although planet formation is thought to be a stochastic process, statistical quantities and occurrence...
currence patterns, e.g. mass distribution or metallicity correlation, presumably reflect underlying processes common to all systems. Any planet formation theory is incomplete if it cannot account for such trends in the sub-Earth population. Historically, the study of exoplanets in previously unexplored regions of parameter space has provoked new ideas: The discovery of “hot Jupiters” (Mayor and Queloz 1995) led to proposals for orbital migration (Lin et al. 1996), that of “super-Earths” (Rivera et al. 2005) kindled interest in volatile-rich “ocean planets” (Kuchner 2003; Léger et al. 2004), and the hot rocky planet CoRoT-7b (Queloz et al. 2009) stimulated the concept of “lava planets” (Léger et al. 2011) and “Chthonian” planets, the remnant cores of evaporated gas giants (Hébrard et al. 2004). STEPS should likewise expand our appreciation for — and demand the explanation of — the diverse outcomes of planet formation.

In this review, we address the capability of both the Kepler space mission (§2) and ground-based Doppler observations (§3) to detect STEPs. In §4 we consider the original (pulsar timing) and one future (microlensing) method by which STEPs can be detected, as well as the potential for discovery of exomoons. In §5 we discuss the predictions of planet formation theory, and in §6 we speculate on the properties of STEPs and how they might be established by follow-up observations. We summarize our conclusions and recommend future studies in §7.

![Fig. 1 Radii and orbital periods of confirmed (blue diamonds) and candidate STEPs (red triangles). The latter, all but one of which are Kepler detections, are included only if they have estimated radii at least 1σ$_{R_p}$ below 1 R$_⊕$ according to the NASA Exoplanet Archive. The void near 1 R$_⊕$ is a result of this criterion. Where uncertainties are unavailable, we include R < 1 R$_⊕$. We equate radii and mass using a relation for low-mass rocky planets with negligible water content (Valencia et al. 2007).]
2 Detection of Sub-Earths by *Kepler*

Since most of the currently known sub-Earth planet candidates were discovered by *Kepler*, it is useful to study the sensitivity of *Kepler* observations to such planets. This will provide an estimate of the number of stars in the *Kepler* sample around which the mission could detect transiting sub-Earth planets as well as identify those stars most suitable for such a search.

The *Kepler* spacecraft was launched in 2009 with the primary goal of discovering an Earth-size exoplanet in the habitable zone of a solar-type star (Borucki et al. 2010; Koch et al. 2010). As of January 2013, the *Kepler* mission has discovered 105 bona fide planets and more than 2700 planetary candidates using the transit detection method, i.e. by detecting the decrease in flux as the planet passes in front of its host star. Most candidates are likely to be planets (Colón et al. 2012; Morton 2012; Fressin et al. 2013), but the stars are either too faint or the planets too small to be confirmed by the radial velocity method (§3). The unsurpassed precision of *Kepler* photometry and the fact that the transit method is sensitive to the cross-section ($\propto R_p^2$) of the planet, not its mass ($\propto R_p^4$, Valencia et al. 2007) makes *Kepler* our most powerful tool for detecting STEPs.

2.1 Direct transit detection

We assess the ability of *Kepler* to directly detect STEPs via transits of their host stars. The transit signal is proportional to $(R_p/R_*)^2$, where $R_*$ is the radius of the star. At a given detection limit for a transit signal, smaller planets can be found around smaller stars. For example, a 0.5 $R_\oplus$ planet produces a signal of $\sim 20$ parts per million (ppm) if it transits a G5 dwarf, but $\sim 50$ ppm if it transits an M2 dwarf. All else being equal, late-type M dwarf stars should be more desirable targets for searches for STEPs. We first consider the fraction of sub-Earths that would be detected around the planet-hosting *Kepler* M dwarfs characterized by Muirhead et al. (2012a) (hereafter M12). These stars have radii and masses inferred from a comparison of spectrocopically-determined effective temperatures $T_{\text{eff}}$ and metallicities with stellar evolution models. These allow us to convert a detection threshold into equivalent planet radii. Furthermore, these stars are likely to host additional planets (Wright et al. 2009; Lissauer et al. 2011), and these planets are also likely to transit because of orbital coplanarity (Sanchis-Ojeda et al. 2012; Hirano et al. 2012).

The radius of the smallest detectable planet $R_p$ with an orbital period $P$ observed for a time $t_{\text{obs}}$ is:

$$R_p = R_* \sqrt{ \left( \frac{P}{t_{\text{obs}}} \right)^{1/2} \frac{S/N}{\text{CDPP}_d} } ,$$  \hspace{1cm} (1)

where the threshold signal to noise S/N for detection is 7.1 (Jenkins et al. 2010; Tenenbaum et al. 2012), and CDPP is the effective Combined Differential Photometric Precision over a time interval $d$ (Koch et al. 2010). CDPP$_d$ is a measure of the noise of a light curve within a specified time interval $d$ and is similar to the standard deviation of the photometry binned over that interval.

To determine the sensitivity of the survey to sub-Earth planets around the M12 stars, we first calculate the transit duration ($d$) for a range of possible planet orbital periods using the stellar masses and radii from M12. To determine CDPP$_d$ we fit a
second-order polynomial in $1/\sqrt{d}$ to the $d = 3, 6, \text{ and } 12$ hour CDPP values of each of the $\sim 168,000$ stars observed by Kepler. Assuming that every planet transits, and that the observing timespan is equal to the total length of the Kepler primary plus extended mission ($t_{\text{obs}} = 6.8$ yr), Kepler should be able to detect transiting sub-Earth-size planets with periods as long as $\sim 60$ days around $\sim 50\%$ of the stars in the M12 catalogue (Fig. 2).

![Graph]

**Fig. 2** Detectable fraction vs. period and planet radius for hypothetical additional planets orbiting planet-hosting stars in the M12 catalogue. All planets are assumed to be on coplanar orbits and transiting. The dashed lines show the best current radial velocity capability ($0.5 \text{ m s}^{-1}$) and future radial velocity capability ($2 \text{ cm s}^{-1}$) for instruments such as CODEX (see §3) assuming the median stellar mass ($0.53 \text{ M}_{\odot}$) of the M12 sample and a planet mass-to-radius relation for rocky planets from Valencia et al. (2007). The detectable fraction is defined as the fraction of M12 stars around which a planet of a given radius and period would produce a detectable ($7.1 \sigma$) transit signal over the course of the extended Kepler mission ($6.8$ yr, see section 2.1).

Although the transit signal for a given planet size is inversely proportional to the square of the stellar radius, the transit signal-to-noise also depends on the noise due to both intrinsic stellar variability and photometric error (Gilliland et al. 2011). The smallest planets can be detected around the smallest, brightest, and most intrinsically quiet stars. All of the stars in the M12 catalogue are early- to mid-M-type stars: Gilliland et al. (2011) shows that only 7% of M dwarfs, but 76% of G5 dwarfs have CDPP$_6 < 50$ ppm. In addition, late-type stars are much less luminous and thus underrepresented in the magnitude-limited Kepler survey.

The results of Gilliland et al. (2011) motivate us to identify the subset of Kepler targets that are best suited for detecting transits of sub-Earth-sized objects. These same

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$^b$ The extended mission may be terminated due to the failure of a second reaction wheel on the spacecraft.
arguments will also apply to any future space-based transit survey if the photometric precision is limited by stellar variability. Since transit signal-to-noise scales inversely with the product of \( R^2 \) and CDPP, we define a parameter \( D \equiv R^2 \text{CDPP} \) to identify the most suitable stars for which to search for small planets. We use CDPP to as our reference because the corresponding orbital period of a transiting planet is 40 d, within the range considered here. (The other available precision metrics are for 3 hr and 12 hr, corresponding to orbital periods of 5 d and 320 d).

Smaller planets can be detected around stars with lower values of \( D \). Figure 3 shows the distribution of \( D \) for those stars observed by Kepler, binned by the \( T_{\text{eff}} \) reported in the Kepler Input Catalogue (KIC; Brown et al. 2011). The curves are cumulative with \( T_{\text{eff}} \) from coolest to hottest: the uppermost curve is the total over all \( T_{\text{eff}} \). These distributions peak near \( D \approx 80 \text{ ppm} \), close to the signal from the single transit of an Earth twin around a solar analog (84 ppm). This means that the signal-to-noise of individual transits of an Earth twin would be \( \sim 1 \) and highlights the challenge of detecting such a planet with Kepler. Planets on shorter-period orbits will produce more transits and are more readily detected. About one quarter of all Kepler targets have \( D < 70 \text{ ppm} \). Figure 3 indicates that no particular spectral type is optimal, although stars with \( 5450 \text{ K} < T_{\text{eff}} < 5700 \text{ K} \) have a \( D \) distribution slightly skewed toward lower values. This contrasts with the common perception that M dwarfs are favorable targets because, among Kepler stars, M dwarfs are fainter and photometrically noisier. However, the stellar radii of very low-mass stars in the KIC catalogue are systematically too large (Muirhead et al. 2012a; Mann et al. 2012). If the radii were corrected, this would push the distribution of \( D \) for the M-dwarfs towards smaller values of \( D \), making them slightly better targets.

In order to estimate the fraction of stars around which sub-Earth-size planets are detectable in the Kepler photometry via transits, we select the 25% (32,721) of stars with the smallest values of \( D \) and calculate the percentage of sub-Earth planets that would be detected if each star was orbited by a planet with a given period. We assume isotropically-oriented orbits, such that the transit probability is \( R_*/a \), where \( a \) is the semi-major axis, using \( R_* \) from the KIC and the scaling relation \( M_* \sim R_*^{0.8} \) (Cox and Pilachowski 2000) to determine \( a \) from \( P \). Figure 4 shows that Kepler should find \( \sim 1\% \) of planets with \( R \sim 1 \text{ R}_\oplus \) out to \( P \sim 80 \text{ d} \) around these stars. Thirty-six sub-Earths found by Kepler orbit at \( 1 < P < 10 \text{ d} \) where the detection efficiency is \( \sim 5\%-10\% \) (Fig. 3).

2.2 Detection by transit timing variations

Additional, non-transiting planets can be detected when mutual gravitational perturbations cause sufficient variation in the ephemeris of the transiting planet (Miralda-Escude 2002; Holman and Murray 2005; Agol et al. 2005). The amplitude of these transit timing variations (TTVs) in the case of an inner transiting planet being perturbed by a longer period companion is (Holman and Murray 2005):

\[
\Delta t \simeq \frac{45\pi}{16} \frac{M_p}{M_*} \frac{P^3 \alpha_e^3}{(1 - \sqrt{2}\alpha_e^{3/2})^2},
\]

where the subscripts 1 and 2 indicate parameters of the transiting and perturbing planet, respectively, \( P \) is the orbital period, \( M_p \) is the perturbing planet mass, \( M_* \) is
the mass of the host star, $a_e = a_1/\sqrt{a_2(1-e^2)}$, and $e$ is the eccentricity. $\Delta t$ depends on the mass of the perturber (not the transiting planet), and sub-Earth-mass perturbers will produce only a very small TTV signal. The amplitude of a TTV signal also depends on the period ratio and orbital eccentricities of the two planets and is maximized when the periods are commensurate. Dynamical simulations show that the maximum TTV signal from an Earth-mass planet will be $\sim 20$ s (Holman and Murray 2005).

*Kepler* can measure the time of transit center with a precision of $\sim 20$ s for the deepest transits of the brightest stars, but for the majority of stars the precision is much worse (Ford et al. 2011). The highest precision that has ever been achieved is $\sim 5$ s using the *Hubble* Space Telescope (Brown et al. 2001; Pont et al. 2007), and ground-based observations can achieve precisions of $\sim 60$ s (Fulton et al. 2011; Maciejewski et al. 2013). Although *Hubble* may be able to detect TTVs due to sub-Earths, the telescope’s short observing window (due to its low Earth orbit) makes it less than ideal for this type of observation. It seems unlikely that TTVs will be a viable method to detect STEPs until the advent of a more capable observatory such as the *James Webb* Space Telescope (JWST).

3 Doppler detection

The radial velocity (RV) or Doppler method was used to discover and confirm the first exoplanet around a main-sequence star (Mayor and Queloz 1995), and is responsible for nearly half of all exoplanet discoveries to date (Schneider et al. 2011). Although this statistic is changing because of the success of transit surveys such as *Kepler*, RV measurements are required to rule out certain false positive scenarios and measure...
planetary mass. For a circular orbit, RV semi-amplitude $K$ scales as

$$K \approx 64 \frac{M_p \sin i}{M_\odot} \left( \frac{P}{1 \text{~d}} \right)^{-1/3} \left( \frac{M_\star}{M_\odot} \right)^{-2/3} \text{~cm~s}^{-1}. \quad (3)$$

where $i$ is the orbital inclination of the planet with respect to the plane of the sky. As of January 2013, the smallest reported signal is 51 cm s$^{-1}$ from a planet with a minimum mass of 1.3 $M_\oplus$ on a 3.2 d orbit around $\alpha$ Cen B (Dumusque et al. 2012, but see Hatzes 2013). This detection was made by the High Accuracy Radial velocity Planet Searcher (HARPS) instrument installed on the ESO La Silla 3.6 m telescope in Chile, which represents the state of the art in operational spectrographs. Other instruments achieve an RV stability in the 1–3 m s$^{-1}$ range (Table 2). This performance falls well short of what is needed to detect Earths or sub-Earths with $P \gg 1$ d around solar-type stars, but leaves open the possibility of discovering or confirming “hot” STEPs on extremely close orbits ($P \sim 1$ d) around M dwarfs (Fig. 2).

Detection of STEPs at larger orbital distances will require greatly improved sensitivity: A 0.5 $M_\oplus$ planet on a 10 d orbit around a 0.53$M_\odot$ star produces a maximum Doppler signal of $\sim 22$ cm s$^{-1}$, or roughly half that of the current best precision reported by HARPS. The same planet with the same orbit around a solar-type star would produce a Doppler signal of only $\sim 14$ cm s$^{-1}$. Although this precision is beyond the abilities of current instruments, there are already plans in place to improve the performance of existing instruments, such as HARPS, and to build new instruments which will achieve the precision needed to detect STEPs. In order to do this, new instruments

**Fig. 4** Detectable planet fraction vs. period and planet radius of the 25% most detection-favorable **Kepler** targets, i.e. smallest $D \equiv R_p^2 \times \text{CDPP}_c$, accounting for transit probability. The sharp rise of the contours (decrease in detectability) at long periods is a result of the geometric probability of transit being very low for long-period planets. The detectable fraction is defined as the fraction of KIC stars around which a planet of a given radius and period would produce a detectable (7.1 $\sigma$) transit signal (see Section 2.1).
must overcome both instrumental and stellar noise. The solutions come from multiple approaches, and we address each below.

Spectrographs mounted directly on telescopes experience flexure, pressure variations, and temperature variations that produce systematic errors. These effects can be minimized by placing the instrument in a temperature-stabilized dewar fed by a fiber from the telescope, as is done with HARPS (Lovis et al. 2006). Imaging a star directly onto a spectrograph slit engenders noise from guiding errors and changes in the point spread function (PSF) (Valenti et al. 1995; Endl et al. 2000). These issues can be partially addressed by high-cadence pointing corrections, but a more elegant solution is to stabilize the PSF by transmitting the light to the instrument by a fiber (e.g., Spronck et al. 2012; Bouchy et al. 2013). Isolating and finely controlling the environment of the instrument is necessary to maintain both short-term (single observation) and long-term (survey-spanning) instrumental precision.

Another source of error is the wavelength calibrator against which Doppler shifts are measured. A molecular iodine gas absorption cell, placed in the beamline, provides a forest of fiducial absorption lines at \( \lambda < 650 \text{ nm} \) (Butler et al. 1996). While iodine works well for observations of solar-type stars, which have significant signal at blue wavelengths, it becomes a limiting factor for Doppler observations of M dwarfs, which have peak emission at redder (\( \lambda > 800 \text{ nm} \)) wavelengths. An alternative gas is ammonia, which has a large number of lines in the \( K (2.2 \mu \text{m}) \) band (Reiners et al. 2010).

An ammonia gas cell is used with the CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES) at the ESO Very Large Telescope (VLT) for radial velocity searches for planets around M dwarfs (Bean et al. 2010).

There are also alternatives to gas absorption cells. The HARPS spectrograph uses the emission lines from a thorium-argon lamp, but such lamps also have fewer lines in the near infrared and the light from the lamp does not follow the exact same path as that from the star. A laser frequency “comb” combined with an etalon interferometer can create a uniform ladder of equally bright emission lines across a selectable wavelength range. Steinmetz et al. (2008) suggest that, with more development, laser combs should permit RV measurements with a precision of \( \sim 1 \text{ cm s}^{-1} \).

The ultimate limit to the Doppler method is intrinsic stellar noise or “jitter” from granulation, oscillations, plages, and star spots. One strategy is to average over these noise terms. Dumusque et al. (2011) conclude that a scheme where three 10-minute spectra are obtained 2 hours apart on each of 10 nights per month yields the best radial velocity precision and minimizes problems from stellar variability.

Forthcoming instruments will take advantage of these technologies and strategies (Table 2). HARPS-North, installed on the Telescopio Nazionale Galileo (TNG) on La Palma Island in the Canary Islands (Cosentino et al. 2012), is based on the design of the original HARPS instrument but will use a laser comb to achieve a precision of \( \sim 10 \text{ cm s}^{-1} \) (Li et al. 2012). The Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO) on the ESO VLT is expected to reach an RV precision of at least 10 cm s\(^{-1}\), with a goal of a few cm s\(^{-1}\) (Pepe et al. 2010). The design specifications of CODEX, planned for the European Extremely Large Telescope, call for <2 cm s\(^{-1}\) RV precision (Pasquini et al. 2010). If there is an equivalent suppression in the effect of stellar “jitter”, such instruments should be able to find STEP’s orbiting close (\( P < 10 \text{ d} \)) to nearby bright stars (Fig. 2). However, estimating the yield of a survey is difficult because of the lack of data on stellar noise at such precision, and thus any empirical means to construct a suitable target catalog of Doppler “quiet”
stars. However, should an instrument such as CODEX achieve \( \sim 2 \, \text{cm s}^{-1} \) precision it could, in principle, detect Mars-size planets with \( P < 100 \, \text{d} \) (Fig. 2).

4 Other Detection Techniques and Sub-Earth Objects

4.1 Pulsar planets

Since the discovery of the three planets of pulsar PSR1257+12, including one of lunar mass, searches of several dozen other millisecond pulsars have revealed no other systems of similar ilk (Wolszczan 2012). Pulsar PSR1719-1328 has a single substellar (\( \sim 2–3 \, M_J \)) companion on a 2.2 hr orbit (Bailes et al. 2011), but this may be the degenerate helium or carbon/oxygen remnant of a former “donor star” (van Haften et al. 2012). Given the exquisite timing stability of millisecond pulsars, the lack of additional discoveries cannot be an artifact of sensitivity. Miller and Hamilton (2001) propose that the scarcity of planets around millisecond pulsars can be explained in terms of the “recycling” hypothesis where accretion of matter from a donor star spins up the pulsar and makes it emit extremely stable, detectable radio signals. Such accretion produces an X-ray luminosity sufficient to vaporize any planets, and Miller and Hamilton (2001) argue that PSR1257+12 must be a rare example of a high primordial spin. Even more problematic is developing a plausible mechanism for the formation of the planets, either via survival of the supernova explosion that created the neutron star, by accretion from the disk resulting from the disruption of a companion or supernova fallback, or by capture from a main-sequence star (Sigurdsson 1993). We refer the reader to the review by Phillips and Thorsett (1994) and references therein, as well as the revisit by Hansen et al. (2009) to this issue. Although additional pulsar planets may be uncovered in the future, their rarity means that they will not significantly contribute to the catalog of known sub-Earths.

4.2 Microlensing

A small planet can also be detected by “microlensing”, i.e. as its host star passes very close to the line of sight between an observer and a more distant star (Mao and Paczynski 1991). The effect of the planet is to break the radial symmetry of the gravitational lens and produce a distinctive, hours-long deviation from the symmetric days-long amplification in the light curve of the background star. Microlensing events are rare and this technique requires simultaneous monitoring of millions of distant stars, e.g. in the Galactic Bulge.

The method is most sensitive to planets with semi-major axes of a few AU, i.e. the angular Einstein radius projected to the typical distance of a lens. Sensitivity to small planets is ultimately limited by the angular size of the background star compared to the Einstein radius of the planet. In principle, monitoring of giant stars in the Bulge permits the detection of planets as low as 1 M\(_\oplus\) (Bennett and Rhie 1996), but because of limited observing cadence and sensitivity, the smallest planet detected to date has a mass of a few Earths (Kubas et al. 2012). Routine detection of Earth-size planets will require a second generation of ground-based microlensing surveys (Wright and Gaudi 2012).
For dwarf stars at the distance of the Bulge, the theoretical detection limit is a few lunar masses. However, these stars will be very faint ($V > 20$), and the projected surface density of such stars towards the Bulge is several per square arc-second. Therefore, a dedicated space telescope that can achieve diffraction-limited, high photometric precision observations is required (Bennett and Rhie 2002; Bennett 2008). Such aspirations may eventually be realized in the form of the Euclid mission (Penny et al. 2012), the Wide Field InfraRed Space Telescope (WFIRST) (Barry et al. 2011) mission, or the NEW-WFIRST mission (Dressler et al. 2012), which should be capable of detecting planets as small as Mars ($\sim 0.1 M_{\oplus}$). In particular, two 2.4 m telescopes, built by the US National Reconnaissance Office and transferred to NASA offer diffraction limited imaging of 0.16 arc-seconds at $\lambda = 1.6 \mu m$ and might triple the yield of Mars-size planets compared to the design reference mission of WFIRST (Dressler et al. 2012).

4.3 Exomoons

Satellites of exoplanets have yet to be discovered but the Copernican idea predicts that the Solar System is not unique in this way. Given that Ganymede, the largest satellite in our Solar System, has only 2.5% of Earth’s mass, it seems likely that satellites in other Solar Systems will also be sub-Earth objects. Satellites can accrete from the circumplanetary disks of giant planets, which accrete inflowing gas and solid material from the circumstellar disk. Dynamical simulations suggest that if a satellite grows large enough it will migrate inward and be accreted by its host planet (e.g., Canup and Ward 2006; Sasaki et al. 2010). Canup and Ward (2006) found that this process restricts the ratio of cumulative satellite mass to planet mass to $\lesssim 10^{-4}$ e.g. $\sim 0.1 M_{\oplus}$ for a Jupiter-mass planet. This limit depends weakly on model parameters including gas surface density, abundance of solids, inflow timescale and migration efficiency. If the Canup and Ward (2006) model is representative of typical circumplanetary disk accretion, we should not expect satellites formed in-situ around Jupiter-mass planets to greatly exceed the mass of Mars. On the other hand, Ogihara et al. (2012) added an inner circumplanetary disk cavity to the model of Canup and Ward (2006), and found that, in some cases, inward migration was inhibited. An inner cavity can be caused by magnetic coupling of the planet to the disk, but it is unclear how frequently this occurs.

Not all exomoons would necessarily form in a circumplanetary disk. The irregular orbits of many Solar System satellites indicate that they were acquired by their giant planet hosts through one of several proposed capture mechanisms. Dynamical simulations by Cuk and Burns (2004) suggest that if a planetesimal encountering a circumplanetary disk experiences sufficient gas drag, capture could occur. Alternatively, binary planetesimals could become separated by the tidal pull of a giant planet resulting in the capture of a single planetesimal. In fact, the inclined retrograde orbit of Neptune’s moon Triton might be the result of the latter mechanism (Agnor and Hamilton 2006). Even if capture events in exoplanet systems are rare, the rate of survival of captured moons might be high. Porter and Grundy (2011) considered the post-capture stability of satellites around non-migrating giant planets in stellar habitable zones and found that about 20-50% of Mars- to Earth-size satellites enter stable orbits. It is conceivable that terrestrial-size planets could also be captured by an inward migrating gas giant. However, simulations are needed to estimate the likelihood of such events as
well as the likelihood of long-term orbital stability. As a gas giant moves closer to its host star, its Hill radius shrinks and stability is limited to tighter orbits.

Close encounters between giant planets might commonly eject their satellites: Gong et al. (2013) performed dynamical simulations consisting of three satellite-hosting giant planets, with varying planet mass, planet eccentricity, satellite mass, and satellite semi-major axis. In \( \approx 75\% \) of their simulations, planet-planet scattering resulted in the ejection of all satellites. If planet-planet scattering is common among giant planets they are unlikely to retain their primordial satellites. The prospect for satellites around hot Jupiters would be especially grim if the orbits of these planets is a result of strong dynamical interactions.

Moon-size or larger satellites could of course form in the manner of the Moon’s proposed origin — from the collision of two (proto)planets. Elser et al. (2011) predict that satellites with \( >0.5 \) lunar masses form around approximately 1 in 12 rocky planets. The most massive satellite produced in their simulations has three lunar masses.

In principle, Kepler can discover massive exomoons in the same manner it finds sub-Earths. An exomoon can transit the host star, adding an additional transit signal differing in phase, amplitude, and duration from that of the planet. Satellites on wide orbits could induce detectable reflex motions in the planet (Kipping et al. 2009), while satellites on close-in orbits are more likely to transit the planet as the planet transits the star. The latter is called a “mutual event” during which the transit signal temporarily decreases (Ragozzine and Holman 2010; Pál 2012). Satellites with large orbital inclinations relative to their host planet’s orbital plane could transit the star even if the planet does not.

Satellites can also be detected by TTVs as well as the transit duration variations (TDVs) that they induce on their planetary hosts. The TTV signal is shifted in phase by \( \pi/2 \) relative to the TDV signal, allowing it to be distinguished from the effect of another planet (Kipping et al. 2009). Moreover, TTV amplitudes scale differently with satellite mass and orbital distance than TDV amplitudes, and these complementary measures thus provide unique solutions for these two parameters. Mass-dependent TTV and TDV detections can be combined with a (radius-dependent) transit signal to calculate the satellite’s bulk density and infer its composition. Kipping et al. (2009) found that, using TTV and TDV measurements alone, Kepler may be sensitive to exomoons \( \geq 0.2 \) M\( _{\oplus} \) or about 0.67 R\( _{\oplus} \) for an Earth-like composition. Hence, Kepler should be able to detect both the transit (§2.1) and the TTV/TDV signals from such a massive exomoon — if they exist.

The Hunt for Exomoons with Kepler (HEK) has identified the most likely hosts of detectable exomoons based on Kepler light curves (Kipping et al. 2013). The light curves of selected stars are compared with planet-only or planet-satellite models in a Bayesian analysis. So far, the HEK team has shown that the 7 most likely candidates are unlikely to have moons comparable in mass to their 2–4 R\( _{\oplus} \) planet hosts (Kipping et al. 2013).

5 Formation of Subterrestrial Planets

According to canonical theory, rocky planets accrete from a disk of gas and dust that surrounds a protostar. In the first \( \sim 10^4 \) years, micron-size dust grains coagulate and settle to the disk midplane. However, growth of particles to sizes larger than a few millimeters cannot be observed and is poorly understood. Laboratory experiments indicate
that collisions of millimeter-size grains rarely lead to sticking and growth under the assumed dynamical conditions within disks (Blum and Wurm 2000; Zsom et al. 2010; Weidling et al. 2012). Moreover, the motion of larger (meter-size) bodies decouples from the gas and they experience a headwind and orbital decay into the star (Weidenschilling 1977a). In theory, meter-size bodies should be lost to the central star in $\sim$100 years (Youdin and Kenyon 2013). Possible mechanisms by which nature overcomes these growth barriers have been proposed (See Chiang and Youdin 2010; Morbidelli et al. 2012; Youdin and Kenyon 2013; Haghighipour 2013 for reviews). Regardless, bodies large enough (km-size) to be impervious to this effect must form by some mechanism. Once mutual gravitation begins to dominate, larger objects experience runaway growth over $10^5$ – $10^6$ years (Morbidelli et al. 2012). Growth of the largest bodies slows down as they accumulate most of the remaining material within a “feeding zone”, becoming lunar-to martian-size protoplanets (Chambers 2006; Kokubo and Ida 1998, 2000). Once the mass in protoplanets exceeds that of planetesimals, their orbits begin to cross (Kenyon and Bromley 2006). Chaotic scattering and collisions ensue for $\sim$100 Myr until a few relatively isolated planets remain.

STEPS might emerge from the final stages of planet formation via the same mechanisms proposed for their Earth- and super-Earth-size brethren: (i) as the in-situ products of constructive and destructive collisions and scattering of smaller planetary embryos (Morbidelli et al. 2012; Kennedy and Kenyon 2008); (ii) from embryos that have migrated inwards as a result of gravitational torques exerted by the protoplanetary disk (“Type-I migration”, Ida and Lin 2010; Terquem and Papaloizou 2007; O’Brien et al. 2006), (iii) by gravitational scattering (Ida and Lin 2010; Kennedy and Kenyon 2008; Raymond et al. 2008), or (iv) shepherding by inward-migrating giant planets (Zhou et al. 2005; Raymond et al. 2006; Fogg and Nelson 2007; Mandell et al. 2007) or super-Earths (Kennedy and Kenyon 2008). A fifth mechanism - evaporation of larger bodies (Valencia et al. 2010), is discussed in §6. The rate of Type-I migration of an object is proportional to its mass (Ward 1997) whereas smaller planets are more susceptible to gravitational scattering and shepherding. For a more detailed review of rocky planet formation see Morbidelli et al. (2012).

Numerical N-body simulations are a popular tool for investigating the late stages of rocky planet formation (Morbidelli et al. 2012). Such simulations consistently produce planets that have masses between those of Mars and Venus over a wide range of orbits (e.g. Walsh et al. 2011; Raymond et al. 2009; Montgomery and Laughlin 2009; Kokubo et al. 2006). These outcomes are plausible examples of other planetary systems produced by the stochastic nature of the planet formation process, suggesting that most STEPs are unlikely to be of similar mass or occupy similar orbits as Mercury or Mars.

The initial mass surface density of the disk is an important parameter of dynamical models and it may determine planet size. One common choice of initial condition is the Minimum Mass Solar Nebula (MMSN; Weidenschilling 1977b; Hayashi 1981). However, the MMSN is not necessarily representative of all disks. For example, Chiang and Laughlin 2012 derive a “Minimum-Mass Extrasolar Nebula” from the population of Kepler-detected super-Earths that is $\sim$5 times denser than the MMSN. Figure 5 shows the average mass of the largest and second-largest planets that form between 0.5 and 1.5 AU in simulations by Kokubo et al. (2006). The authors varied the mass surface density of the disk at 1 AU ($\Sigma_1$) while maintaining a power-law radial surface density profile with index -3/2. The MMSN corresponds to $\Sigma_1 = 7$ g cm$^{-2}$. The average masses follow power laws with disk surface density having indices close to unity. If low-
mass stars have disks of lower surface density, then the results of Kokubo et al. (2006) predict that small planets are most common around M-dwarfs, at least at 0.5–1.5 AU. However, the evidence for a relation between disk surface density and stellar mass is tentative (Williams and Cieza 2011; Andrews et al. 2013).

The limited supply of disk material and hence the surface density likely governs the in-situ formation of close-in and especially detectable planets. Raymond et al. (2007) show that a MMSN disk rarely forms planets more massive than Mars within ≃0.1 AU of late M-dwarfs. However, Montgomery and Laughlin (2009) find that a disk three times denser than the MMSN instead produces 3-5 planets with an average mass of 0.7–0.8 M⊕. These results suggest that the formation of STEPs depends on surface density. However, Kepler observations show that the occurrence of Earth- to Neptune-size planets does not depend on stellar metallicity, a potential proxy for disk surface density (Buchhave et al. 2012; Mann et al. 2013).

STEPS may also migrate to close-in orbits after forming at larger orbital distances. Kennedy and Kenyon (2008) conclude that the minimum mass of a planet able to migrate to a short-period orbit is proportional to the distance at which ice condenses in the disk (the “snow line”). This distance scales with stellar luminosity and hence stellar mass. The same study shows that planets also tend to scatter to smaller orbital distance around low-mass stars, again suggesting that low-mass stars might commonly host detectable STEPS. Because (Type I) orbital migration scales with planet mass and mutual gravitational interactions will preferentially scatter less massive planets, we expect scattering to be more efficient than migration in dispersing the orbits of STEPS.

Fig. 5 Mean masses ⟨M⟩ of the largest (filled circles) and second largest (open circles) planets formed in simulations of rocky planet formation as a function of disk surface density (Kokubo et al. 2006). The disk surface density depends on radius as a power-law with index -3/2, and is Σ₁ at 1 AU. Best-fit power law relations between Σ₁ and ⟨M⟩ have indices of 1.1 and 0.97 (solid and dashed lines, respectively).
6 Properties of Subterrestrial Planets

Although our Solar System lacks objects with radii between that of Mars and Venus, the diversity among smaller bodies (e.g., Ganymede, Titan, Mercury, and Mars) suggests that STEPs might have diverse characteristics depending on composition, distance from the star, and contingencies such as giant impacts. While there are many properties of such bodies that are of interest, we focus on two that may be ascertainable in the near future: mean density, and the presence or absence of an atmosphere.

The mean density $\bar{\rho}$ of a planet can be estimated if both radius and mass are measured (by the transit and Doppler methods, respectively). These can be compared with theoretical mass-radius relations to infer composition (e.g., Valencia et al. 2007; Seager et al. 2007; Grasset et al. 2009; Rogers and Seager 2010). Although such interior models have not been applied to STEPs per se, there have been detailed comparisons of similar models with Mercury (Hauck et al. 2013) and Mars (Sohl et al. 2005). Comparison with STEPS will be limited by Doppler precision (discussed in §3), sensitivity to planet radius and hence stellar radius ($\geq 3\%$ Torres et al. 2010), and degeneracies between composition and mean density (Rogers and Seager 2010). Because of these limitations, observations will likely be able to discriminate only between the most extreme compositions, i.e. very volatile-rich, rocky, or metal-rich planets.

Mercury, as the Solar System’s smallest and innermost planet, is arguably the most appropriate analog to those sub-Earths that can be detected by the transit ($\S$2) and Doppler ($\S$3) methods. Mercury’s salient bulk properties are a comparatively large iron core comprising most of its volume and mass (Hauck et al. 2013), and a lack of volatiles or substantial atmosphere. Whether its oversized core reflects a non-chondritic composition for the primordial disk close to the Sun (Lewis 1972; Weidenschilling 1978; Ebel and Alexander 2011), or is a consequence of removal of most of the silicate mantle by a giant impact (Benz et al. 1988, 2007; Gladman and Coffey 2009) is debated. Both of these mechanisms are more effective on orbits closer than Mercury ($P = 88$ d), where temperatures in a planet-forming disk and the kinetic energy of impacts, which scales with orbital velocity, are higher. This implies that STEPs close to their host stars may have comparatively large cores as well.

Like Mercury, STEPs on close-in orbits are likely to lack any substantial atmosphere because of their weak gravity and heating of their upper atmospheres by stellar X-ray, extreme ultraviolet (EUV) and Lyman-$\alpha$ radiation. Rapid atmospheric escape is predicted for their more massive super-Earth counterparts (Tian 2009; Pierrehumbert and Gaidos 2011). In the limit that the thermal speeds of atoms become comparable to escape speeds, hydrodynamic escape ensues and mass loss rate is limited only by the rate at which energy is absorbed by the atmosphere:

$$\dot{M} = \frac{3\epsilon F}{4G\bar{\rho}},$$

where $F$ is the incident flux absorbed by the atmosphere, $G$ is the gravitational constant, and $\epsilon$ is an efficiency factor that accounts for the inflation of the atmosphere and radiative, conductive, and evaporative cooling. In this regime, absorption of energy $E$ per unit area results in a loss of atmosphere (in units of pressure) of $E/(4\pi R_p)$. Given realistic models of the evolution of the X-ray and UV output of dwarf stars (Ribas et al. 2005; Sanz-Forcada et al. 2011), a Mercury-size planet on a 10-day orbit around its host star is expected to lose thousands of bars of atmosphere over billions of years.
Hydrodynamic escape will occur from the top of the atmosphere (the exobase) only if it is hot enough and the Jeans parameter \( \lambda = \frac{GM_p \mu}{R_e k_B T} \), the ratio of the gravitational potential to the thermal energy, is \(< 2.8 \) (Johnson 2010), where \( \mu \) is the atomic mass, \( R_e \) is the distance of the exobase from the planet’s center, and \( k_B \) is the Boltzmann constant. As the thermal energy approaches the escape energy, the atmosphere inflates, \( R_e > R_p \), and the escape energy decreases. Approximating this inflation as \( R_e \approx R_p + h \), where \( h = k_B T R_p^2 /(GM_p \mu) \) is the atmospheric scale height, the required exobase temperature is \(~0.29GM_p \mu/(R_p k_B)\). Under all plausible conditions, the light elements H and He will hydrodynamically escape from close-in planets, carrying some heavier elements with them.

A more germane question is whether hydrodynamic escape continues when H and He are exhausted, e.g., by the atomic oxygen produced by dissociation in a CO\(_2\)-dominated Venus-like atmosphere. For atomic oxygen on Venus, the required temperature is \(3 \times 10^4 \) K, but only \(~5000 \) K on a planet the size of Mercury. Figure 6 plots the \( \lambda = 2.8 \) condition for planets with CO\(_2\) atmospheres and the expected combination of X-ray, EUV and Lyman-\( \alpha \) irradiation (Ribas et al. 2005; Sanz-Forcada et al. 2011) for Sun-like (solid lines) and M0 dwarf (dashed lines) stars at three stellar ages. Hydrodynamic escape (\( \lambda < 2.8 \)) occurs to the lower left of each boundary. These calculations assume that all incident X-ray plus UV (XUV) energy is absorbed at the top of the atmosphere and conducted downward, principally by atomic oxygen, to the homopause, then radiated away in the infrared by CO\(_2\). We follow the procedure in Pierrehumbert and Gaidos (2011), except that by assuming a constant thermal conductivity \( k \), an analytical solution is available for the required irradiation \( q \) as a function of \( \lambda \):

\[
q = \frac{GM_p \mu k}{R_p^2 k_B T_0} \ln \left( \frac{\sigma R_p p_0}{Xk_B T_0} \right) \left[ \ln \frac{GM_p \mu}{X R_p k_B T_0} \right]^{-1},
\]

where \( p_0 \) and \( T_0 \) are the pressure and temperature at the homopause, and \( \sigma \) is the collision cross-section. We calculate the \( k \) of atomic O using Dalgarno and Smith (1962), assume a homopause pressure like that of Venus (\(10^{-3} \) Pa) and homopause temperature equal to the planet’s equilibrium temperature, and adopt \( \sigma = 2 \times 10^{-19} \) m\(^2\) (Tully and Johnson 2001). Equation 5 approximately reproduces the Jeans parameter for O on current Venus (\( \lambda = 260 \)) and predicts that it lost atmosphere by hydrodynamic escape prior to 3.5 Ga (if indeed it had a CO\(_2\) atmosphere). It also predicts the hydrodynamic escape of CO\(_2\) from Mars in the past. Mercury would have suffered hydrodynamic escape of any CO\(_2\) atmosphere throughout its history. Any sub-Earth on a closer orbit would have experienced yet greater loss. This is in addition to any removal by the stellar wind (Zendejas et al. 2010) or impacts (Ahrens 1993).

The presence or absence of a substantial atmosphere might be discernable by follow-up observations, at least if the planet is very close to its star, very hot, and tidally locked. By detecting the infrared emission from the planet and measuring its variation with phase, the redistribution of heat around a synchronously rotating planet can be estimated (e.g., Gaidos and Williams 2003; Lewis et al. 2010; Cowan and Agol 2011; Demory et al. 2012). Planets lacking an atmosphere will have no redistribution, their substellar hemispheres will be hotter, and their phase curves more pronounced. Planets with a thick, circulating atmosphere will have cooler illuminated hemispheres because some of the heat is transferred to the night side, and their emission will exhibit little or no variation with phase. The boundary between these two regimes has not been theoretically established for planets on close-in orbits but is probably equivalent to
Fig. 6 Combinations of rocky planet radius and orbital period for which the Jeans parameter λ of a CO₂ atmosphere is 2.8, the condition for hydrodynamic escape. The combined fluxes of stellar X-ray, EUV, and Lyman-α radiation at ages of 0.5, 1, and 4.5 Gyr are used [Ribas et al. 2005; Sanz-Forcada et al. 2011]. Solid lines are for a Sun-like star and dashed lines are for an M0 dwarf star host. Atmospheres below and to the left of these lines will have λ < 2.8 and be hydrodynamically escaping. The inner planets of the Solar System are plotted.

a surface pressure of a fraction of a bar. The emission from an unresolved transiting planet can be detected by differencing the signal in and out of secondary eclipse. In exceptional cases, it might be possible to determine the planet's phase curve by measuring the small variation in total flux over a complete orbit.

The most promising (and perhaps only) tool with which to carry out such observations will be JWST using either the Near Infrared Camera (NIRCam) or the Mid Infrared Instrument (MIRI) [Clampin 2012]. Figure 7 shows estimated detection thresholds vs. orbital period for sub-Earths orbiting an M0 dwarf star at 10 pc. Breaks in the curves mark transitions between the regimes where one instrument is favored over the other. Two cases are considered: a Venus-like planet with an albedo of 0.9 and efficient heat redistribution (black curves), and a Mercury-like planet with an albedo of 0.068 and no heat redistribution (grey curves). For each case, we calculate a 1σ detection threshold in terms of the minimum angular radius of the planet, i.e. its physical radius at a distance of 10 pc (solid curves). We assume blackbody emission, a 10^4 s integration and the sensitivities from the JWST website. In principle, JWST can detect the thermal emission from very small hot planets. However a more relevant measure of sensitivity is the accuracy with which the stellar signal can be subtracted, i.e. the photometric stability. The dotted curves in Fig. 7 correspond to a fractional detection threshold of 10^{-4} relative to the host star. This level of stability has been achieved with the Spitzer infrared space telescope [Demory et al. 2012]. The two dashed curves

http://www.stsci.edu/jwst/science/sensitivity/jwst-phot
are for a hypothetical stability of $10^{-5}$ (the actual stability will not be known until JWST is in space). It appears that sub-Earths can be detected by JWST only if its stability significantly exceeds that of Spitzer and only if the planets lack substantial atmospheres.

**Fig. 7** Detection by differential photometry of an eclipsing STEP around a M0 dwarf star at 10 pc with the James Webb Space Telescope and either MIRI or NIRCam. Two cases are considered: a Venus-like albedo and efficient re-distribution of heat around the planet (black lines), and a Mercury-like albedo, no redistribution of heat, and isotropic emission (grey lines). The solid lines are the $10\sigma$ detection of an isolated source, while the dotted and dashed lines are the detection limits if the stellar signal is removed with a photometric accuracy of $10^{-4}$ (typical of Spitzer observations) or $10^{-5}$. The actual stability of these instruments will not be known until JWST is launched.
Table 1  Confirmed and Candidate Sub-Earths (STEPs)\(^a\)

| Name          | \(R_p\) (\(R_\oplus\)) | \(M_p\) (\(M_\oplus\)) | Period (d) | Method | Reference  |
|---------------|-------------------------|--------------------------|------------|--------|------------|
| Kepler-20c\(^b\) | 0.87                    | 0.59                     | 6.10       | transit | F12        |
| Kepler-37b    | 0.30                    | 0.01                     | 13.37      | transit | BA13       |
| Kepler-37c    | 0.74                    | 0.52                     | 21.30      | transit | BA13       |
| Kepler-42b    | 0.78                    | 0.39                     | 1.21       | transit | M12        |
| Kepler-42c    | 0.73                    | 0.30                     | 0.45       | transit | M12        |
| Kepler-42d    | 0.57                    | 0.12                     | 1.87       | transit | M12        |
| Kepler-62c    | 0.54                    | 0.10                     | 12.44      | transit | BO13       |
| PSR B1257+12 A| 0.36                    | 0.02                     | 25.27      | pulsar  | W94        |

| Candidate planets\(^c\) |
|--------------------------|
| KIC 12557548\(^d\)       | 0.38                    | 0.03                     | 0.65       | transit | R12        |
| KOI 55.01\(^e\)          | 0.76                    | 0.35                     | 0.24       | transit | C11        |
| KOI 55.02\(^a\)          | 0.87                    | 0.59                     | 0.34       | transit | C11        |
| KOI 82.04                | 0.70                    | 0.26                     | 7.07       | transit | NEA13      |
| KOI 82.05                | 0.52                    | 0.08                     | 5.29       | transit | NEA13      |
| KOI 251.02               | 0.82                    | 0.47                     | 5.77       | transit | NEA13      |
| KOI 283.02               | 0.84                    | 0.51                     | 25.52      | transit | NEA13      |
| KOI 321.02               | 0.84                    | 0.51                     | 4.62       | transit | NEA13      |
| KOI 430.02               | 0.77                    | 0.37                     | 9.34       | transit | NEA13      |
| KOI 568.02               | 0.74                    | 0.32                     | 2.36       | transit | NEA13      |
| KOI 605.02               | 0.61                    | 0.15                     | 5.07       | transit | NEA13      |
| KOI 672.03               | 0.55                    | 0.10                     | 0.57       | transit | NEA13      |
| KOI 952.05               | 0.86                    | 0.56                     | 0.74       | transit | NEA13      |
| KOI 1499.02              | 0.66                    | 0.20                     | 0.84       | transit | NEA13      |
| KOI 1612.01              | 0.78                    | 0.39                     | 2.47       | transit | NEA13      |
| KOI 1618.01              | 0.77                    | 0.37                     | 2.36       | transit | NEA13      |
| KOI 1619.01              | 0.80                    | 0.43                     | 20.67      | transit | NEA13      |
| KOI 1692.02              | 0.84                    | 0.51                     | 2.46       | transit | NEA13      |
| KOI 1964.01              | 0.73                    | 0.30                     | 2.23       | transit | NEA13      |
| KOI 1977.02              | 0.69                    | 0.24                     | 7.42       | transit | NEA13      |
| KOI 2006.01              | 0.88                    | 0.61                     | 3.27       | transit | NEA13      |
| KOI 2013.01              | 0.86                    | 0.56                     | 2.41       | transit | NEA13      |
| KOI 2029.02              | 0.82                    | 0.47                     | 10.06      | transit | NEA13      |
| KOI 2059.01              | 0.80                    | 0.45                     | 6.15       | transit | NEA13      |
| KOI 2079.01              | 0.66                    | 0.20                     | 0.69       | transit | NEA13      |
| KOI 2169.04              | 0.50                    | 0.07                     | 2.19       | transit | NEA13      |
| KOI 2247.01              | 0.89                    | 0.64                     | 4.46       | transit | NEA13      |
| KOI 2421.01              | 0.72                    | 0.29                     | 2.27       | transit | NEA13      |
| KOI 2426.01              | 0.79                    | 0.41                     | 4.16       | transit | NEA13      |
| KOI 2527.01              | 0.57                    | 0.12                     | 1.39       | transit | NEA13      |
| KOI 2657.01              | 0.60                    | 0.14                     | 5.22       | transit | NEA13      |
| KOI 2693.01              | 0.70                    | 0.26                     | 4.08       | transit | NEA13      |
| KOI 2693.03              | 0.66                    | 0.20                     | 6.83       | transit | NEA13      |
| KOI 2792.01              | 0.61                    | 0.15                     | 2.13       | transit | NEA13      |
| KOI 2838.02              | 0.61                    | 0.15                     | 4.77       | transit | NEA13      |
| KOI 3083.03              | 0.59                    | 0.13                     | 8.29       | transit | NEA13      |
| UCF-1.01                | 0.66                    | 0.20                     | 1.37       | transit | S12        |
| UCF-1.02                | 0.65                    | 0.19                     | —          | transit | S12        |

\(^a\) Assuming \(M/M_\oplus=(R/R_\oplus)^3\). (3.817) appropriate for an Earth-like composition (Valencia et al. 2007).
\(^b\) BA13: Barclay et al. (2013), BO13: Borucki et al. (2013), C11: Charpinet et al. (2011), F12: Fressin et al. (2012), M12: Muirhead et al. (2012b), NEA13: NASA Exoplanet Archive (January 2013), R12: Rappaport et al. (2012), S12: Stevenson et al. (2012), W94: Wolszczan (1994).
\(^c\) Quoted \(M_p\) and \(R_p\) are lower limits.
Table 2  Current and Future Spectrographs for Radial Velocity Measurements.

| Instrument   | Precision (cm s$^{-1}$) | First Light | λ (µm) | Resolution | Reference               |
|--------------|--------------------------|-------------|--------|------------|-------------------------|
| Keck-HiRES  | 100                      | 1996        | 0.3–1.0| 85,000     | Butler et al. (1996)    |
| UCLES        | 300                      | 1998        | 0.48–0.86| 45,000     | Butler et al. (2001)    |
| HDS          | 300                      | 2000        | 0.35–0.65| 150,000    | Kambe et al. (2008)     |
| HARPS        | 50                       | 2003        | 0.38–0.69| 115,000    | Kupperschmidt et al. (2004) |
| SOPHIE       | 200                      | 2006        | 0.38–0.69| 75,000     | Bonfils et al. (2007)   |
| CHRONIS      | 7                        | 2011        | 0.45–0.89| 120,000    | Schwab et al. (2012)    |
| HARPS-N      | 50                       | 2012        | 0.38–0.69| 115,000    | Cosentino et al. (2012) |
| APF-Levy     | ~200                     | 2013        | 0.3–0.65 | 73,000     | Radovan et al. (2010)    |
| APF-HWS      | ~100                     | 2014        | 0.38–0.69| 100,000    | A. Howard, priv. comm. |
| ESPRESSO     | ~10                      | 2016        | 0.35–0.72| 150,000    | Pepe et al. (2010)      |
| CODEX        | ~2                       | 2025        | 0.37–0.72| 150,000    | Pasquini et al. (2016)  |

$^a$ Expected performance

$^b$ In commissioning phase
Removal of mass from sub-Earths may not stop with a CO$_2$ atmosphere. On close-in, tidally-locked planets, substellar surface temperatures are $T \approx 2800(L_\star/L_\odot)^{1/4}(P/1\text{d})^{-1/3}$ where $L_\star$ is the stellar luminosity and a weak dependence on stellar mass is ignored, and a Mercurian albedo (0.068) is assumed. If temperatures exceed the melting point of silicates, a magma “sea” would be present (Léger et al. 2011), and a tenous silicate vapor (SiO, O, and Si) atmosphere would form (Miguel et al. 2011). Continuous escape of this atmosphere would cause gradual mass loss and may have lost about half of its mass. This phenomenon would occur even more readily on smaller planets. Extreme rates of evaporation and a coma of silicate condensates have been proposed to explain the variable transit depth of whatever object orbits the Kepler star 12557548 with a period of 0.65 d (Rappaport et al. 2012).

In this scenario, the silicate mantles of sub-Earths close to solar-type stars may largely evaporate. As evaporation proceeds, the residual mantle, mixed by melting, would become steadily enriched in more refractory, heavier elements. It could eventually founder and/or dissolve into the core, whereupon the object would become an “iron planet”, a naked core with a relatively high mean density. Without a comparatively light element such as O, hydrodynamic escape would halt, although the stellar wind might continue to erode an iron vapor atmosphere. This scenario would not unfold around M dwarfs with $L_\star$ as low as $10^{-4}L_\odot$; the equilibrium temperatures of sub-Earths around such stars would be up to $10 \times$ cooler and they would retain their silicate mantles.

7 Discussion

Over the past two decades, successive discoveries enabled by improvements in ground-based instruments and space missions such as Hubble, Spitzer, CoRoT, and Kepler have uncovered brown dwarfs, Jupiter-like gas giants, volatile-rich Neptunes, “super-Earths”, and now Earth-size and presumably rocky planets. The discovery and characterization of sub-Earths, planets with masses significantly less than that of Earth, is the next and perhaps ultimate leg of the scientific journey to enumerate the worlds on close-in orbits around main-sequence stars. This step has just begun, but we can already draw the following conclusions:

- Several dozen confirmed or candidate sub-Earths have already been discovered by Kepler (plus 3 others by the Arecibo telescope and Spitzer). We expect that number to grow as the remaining Kepler data is analyzed. Studies of Kepler transit light curves may also reveal exomoons, if sufficiently massive ones exist.

- Enumeration of Kepler sub-Earths will determine whether the planet distribution with radius remains flat (Pressin et al. 2013), rises, or falls below $\sim 1\text{ R}_\oplus$ (Petigura et al. 2013). Based on the number of Kepler discoveries to date ($\sim 40$), and a detection efficiency of 5% among the $\sim 33,000$ most suitable stars (Fig. 4), we estimate that at least 2–3% of stars have planets with $0.5\text{ R}_\oplus < R_p < 1\text{ R}_\oplus$ and $P < 10\text{ d}$.

Cameron (1985) and Fegley and Cameron (1987) proposed that the mantle of Mercury was evaporated, but this is inconsistent with the MESSENGER estimate of volatile radioactive potassium in the Mercurian crust (Peplowski et al. 2011).
Sub-Earths are at the limit of Kepler’s detection threshold and any estimate of their occurrence is sensitive to completeness for very small signals, which is still being determined (Petigura et al. 2013). Moreover, the estimated radii of transiting planets depend on the radii of the host stars; those of Kepler targets are being refined as stellar parameters are measured and improved models are applied (Muirhead et al. 2012a; Mann et al. 2012). As a result, our estimate of 2–3% should be considered very tentative and probably a lower limit.

With foreseeable instruments, only STEPs with orbital periods of a few days will be detectable by Doppler (Fig. 2). Kepler stars are too faint for observations of such precision, but it is conceivable that a sample of nearby, much brighter stars could be interrogated by the Doppler method and the two populations compared by statistical techniques (e.g., Gaidos et al. 2012). The occurrence of close-in STEPs could be compared with the number of such objects detected on wider orbits by a microlensing mission such as WFIRST or NEW-FIRST. Such a study would investigate whether sub-Earths preferentially form on close-orbits, or are dynamically scattered onto distant orbits by their more massive counterparts.

Planet formation theory predicts that the surface density of disks influences the size of planets that form in-situ. This linkage may be difficult to reconcile with the apparent independence of small (Earth- to Neptune-size) planet occurrence and host star metallicity, unless migration is common. Determining whether or not these parameters remain independent in the sub-Earth regime, where orbital migration is expected to be less efficient, will help resolve this apparent discrepancy.

If the mass or surface density of planet-forming disks scales with that of the star, then M dwarfs may preferentially host sub-Earths, boding well for their detection (Fig. 2). However, this premise is only weakly supported by the available data and the occurrence of small planets may not depend on stellar mass (Fressin et al. 2013), as was originally thought (Howard et al. 2012). The Atacama Large Millimeter Array (ALMA) will help to clarify any relation between surface density and stellar mass in the context of planet formation. Other millimeter arrays have already yielded masses and surface density profiles of many tens of disks by measuring continuum dust emission, e.g. Isella et al. (2009); Guilloteau et al. (2011). ALMA is expected to increase the yield to hundreds or thousands of disks on account of its order of magnitude better sensitivity and angular resolution (Williams and Cieza 2011).

STEPs may be diverse objects with compositions that reflect initial conditions, formation mechanism, and environment. Sub-Earths close to their parent stars may be rich in water and other volatiles if they originated on wider orbits past the “snow line” and subsequently migrated or were scattered inwards. However, stellar XUV heating and winds are expected to remove their atmospheres (Fig. 6), and, around solar-type stars, the silicate mantles of these planets may evaporate, leaving bare iron cores. Indeed, some sub-Earths may be the product of evaporation of more massive planets. Observations of nearby transiting sub-Earths by JWST may be able to discriminate between tidally-locked planets lacking atmospheres, which will be hotter and brighter, and those with atmospheres, which will be fainter and per-
haps undetectable (Fig. 7).

The immediate scientific return from the study of sub-Earths will be tests of models of planet formation and evolution. Descriptions of their occurrence and distributions with mass and orbital period is essential for a complete description of the planetary kingdom, and any over-arching theory must explain them. The possible role of sub-terrestrial planets as habitats for life should also not be overlooked. Although sub-Earths on very close orbits may not be suitable abodes for life, those further out may orbit in the circumstellar habitable zone and retain atmospheres and water. We who inhabit a comparatively small planet around a “dwarf” star should not presume that one Earth mass is the optimum for life.

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