Kepler-78 and the Ultra-Short-Period Planets

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Abstract

Compared to the Earth, the exoplanet Kepler-78b has a similar size (1.2 $R_\oplus$) and an orbital period a thousand times shorter (8.5 hours). It is currently the smallest planet for which the mass, radius, and dayside brightness have all been measured. Kepler-78b is an exemplar of the ultra-short-period (USP) planets, a category defined by the simple criterion $P_{\text{orb}} < 1$ day. We describe our Fourier-based search of the \textit{Kepler} data that led to the discovery of Kepler-78b, and review what has since been learned about the population of USP planets. They are about as common as hot Jupiters, and they are almost always smaller than 2 $R_\oplus$. They are often members of compact multi-planet systems, although they tend to have relatively large period ratios and mutual inclinations. They might be the exposed rocky cores of “gas dwarfs,” the planets between 2–4 $R_\oplus$ in size that are commonly found in somewhat wider orbits.

Keywords: planets, time-series photometry

1. Introduction

One of the earliest surprises of exoplanetary science was the existence of planets with very short orbital periods. The main pre-exoplanet theory of planet formation predicted that gas giant planets like Jupiter could only form in wide orbits, more than 2–3 times the size of Earth’s orbit around the Sun. Then in 1995, the star 51 Pegasi was found to host a Jupiter-mass planet with an orbit only 5% of the size of Earth’s orbit\textsuperscript{3}. The planet rushes around the star every 3.5 days, an orbital period far shorter than Jupiter’s 4300-day period, or even Mercury’s 88-day period. How planets attain such short periods is the oldest unresolved problem in the field.

After 51 Peg, a good place to continue the story is in 2003 with the discovery of OGLE-TR-56b\textsuperscript{4} (see Figure \textbf{1}). The initial report of this planet was met with skepticism because of the unusually small orbital distance of 0.023 AU and short orbital period of 1.2 days. Practitioners of the Doppler technique wondered why the very first planet to emerge from transit surveys would have such a short period while the longstanding Doppler surveys had not yet found any such planets.
The resolution of this problem was that transit surveys are even more strongly biased toward short periods than Doppler surveys \[5\]. Consider a transit survey in which all the nearby stars within some field of view are repeatedly imaged, allowing the flux \( F \) of each star to be measured with a fractional uncertainty proportional to \( F^{-1/2} \). If all the transit signals exceeding a certain signal-to-noise threshold can be detected, then the number of stars for which a planet of period \( P \) would produce a detectable transit signal scales as \( P^{-5/3} \) \[6, 5\]. A survey designed to search a certain number of stars for Earth-sized planets with a period of 365 days — such as the Kepler survey — is capable in principle of searching \((365)^{5/3} \approx 19,000\) times as many stars for Earth-sized planets with a period of 1 day. Hence, it is possible to find very short-period planets even if they are exceedingly rare.

A transit survey with the Hubble Space Telescope in 2004 led to the detection of five giant-planet candidates with periods shorter than one day, which the authors referred to as “ultra-short-period planets” \[7\]. However, it was difficult to have much confidence that these candidates were truly planets, because of the limited amount of data collected (7 days) and the faintness of the host stars (\( V = 22–26 \) mag). As ground-based transit surveys made further progress, it became clear that giant planets with such short periods are very rare. By early 2018, the ground-based transit surveys had discovered 68 giant planets with periods between 2 and 3 days, but only 37 with periods between 1 and

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Figure 1: Orbital periods of planets discovered through the Doppler and transit methods, versus the year of publication. Data were obtained from exoplanets.org and other catalogs in the literature \[1, 2\]. Small random shifts have been applied to the horizontal positions to allow the data points to be more clearly distinguished.
2 days, and a mere six with periods shorter than one day. This is despite the strong selection bias favoring the shortest periods.

The next major advance came in 2009 during the European *Corot* mission, the first spaceborne transit survey. That year saw the announcement of Corot-7b [8], which was then the smallest known transiting planet ($1.7 \, R_⊕$) and had the shortest known orbital period (0.85 days). A couple of years later, the NASA *Kepler* mission found a similar planet, Kepler-10b, with a radius of $1.4 \, R_⊕$ and an orbital period of 0.84 days [9]. In between these discoveries was a curious episode involving the innermost planet of the 55 Cnc system. The planet was initially discovered through the Doppler technique [10], [11], but the period was misidentified as 2.8 days due to aliasing. Subsequent analysis of the Doppler data [12] and the detection of transits with space-based photometry [13], [14] showed that the true period is 0.74 days.

For Sun-like stars, it is now clear that planets with periods shorter than one day occur just as frequently as hot Jupiters with periods ranging from 1 to 10 days. The reason that the ultra-short-period (USP) planets had previously escaped detection is that they are small, and produce signals that are difficult to detect without the precision of space telescopes. The USP planets have also been called “hot Earths,” or more evocatively, “lava worlds” [15], as their dayside surface temperatures are higher than the melting point of most rock-forming minerals. The current record holder is KOI-1843.03, which circles its star every 4.2 hours [16], [17]. Not far behind is K2-137b, with an orbital period of 4.3 hours [19].

When trying to understand a process as complex as planet formation, the most extreme cases are often the most revealing. This is one reason why the study of USP planets is rewarding. They may help us to understand the formation and orbital evolution of short-period planets, as well as star-planet interactions, atmospheric erosion, and other phenomena arising from strong irradiation and strong tidal forces. In addition there are practical advantages to studying USP planets. They are easier to detect than planets of the same size in wider orbits. Their masses and sizes, the most basic inputs to theories of planetary interiors, are easier to measure. They are sometimes hot enough to emit a detectable glow, enabling observations to determine their surface temperature and reflectivity, which is usually impossible for wider-orbiting planets.

The defining criterion of $P_{\text{orb}} < 1$ day is arbitrary. We chose it because 1 is a nice round number, and because planets with such short periods were relatively unexplored at the time of our survey. Nature does not seem to produce any sharp astrophysical distinction between planets just inside or outside of the one-day boundary. A more meaningful boundary might be at about 10 days, beyond which we start to see differences in the planetary occurrence rate and the mean metallicity of the host stars.

In the spirit of this special issue, Section 2 tells the story of Kepler-78b, a planet with Earth-like proportions and an orbital period of 8.5 hours. This planet is important because it is one of the very smallest planets for which both the mass and radius have been measured to better than 20%. It is also the smallest planet for which the

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1Even though no *Kepler* number has been assigned, KOI-1843.03 is likely to be planet. The signal was validated as a probable planet through the usual tests [17]. In addition, any sources with multiple detected transit signals, such as KOI-1843, are likely to represent genuine planetary systems [13].
brightness of the dayside has been determined, through the detection of planetary oc-
cultations. Kepler-78b was one of the first USP planets that emerged from our sys-
tematic search through the Kepler data. We also take this opportunity, in Section 3, to 
review the searches undertaken by other groups, and the growing collection of related 
investigations into this enigmatic population of planets. Section 4 describes some other 
intriguing ultra-short-period phenomena that might, or might not, be related to planets.

2. Kepler-78

The first appearance in the literature of the star now known as Kepler-78 is in the 
second data release of the Kepler Eclipsing Binary catalog [20], published on October 
12, 2011. It was listed with Kepler Input Catalog (KIC) number 8435766, and deemed 
a detached eclipsing binary with a period of 0.71 days (17 hours). We do not know 
what led to this classification, or why the period was found to be twice as long as the 
true value. Occasional errors of this type are to be expected in any catalog based on 
automated analysis of a large database. In any case, we were unaware of this entry in 
the eclipsing binary catalog. The star came to our attention through a different route.

We had been searching the Kepler data for transiting planets based on the Fourier 
Transform (FT) of the light curve, instead of the more widely used Box-fitting Least 
Squares (BLS) spectrum [21]. Our motivation was to perform a complementary search 
for planets in a regime where the standard Kepler pipeline was having difficulty at that 
time. The BLS method was invented specifically for the detection of transit signals: 
brief drops in brightness modeled as a “box” (rectangular-pulse) function with duration 
$T$ and period $P$. The motivation for the FT method might not be obvious, because 
the FT of a box function has power spread over many harmonics in addition to the 
fundamental frequency. Specifically, it consists of a series of peaks with $f_n = n/P$, 
modulated by the amplitude function

$$A(f) = \frac{T \sin(\pi f T)}{\pi f T}$$

Most of the power is concentrated in the frequency range from zero to the first null at 
$1/T$, within which the number of harmonics is approximately $P/T$. For a transiting 
planet around a Sun-like star,

$$\frac{P}{T} \sim 500 \left( \frac{P}{1 \text{ year}} \right)^{2/3}.$$  

(2)

Splitting the signal among hundreds of harmonics sound like a terrible idea. The peaks 
would be easily lost in the noise. But for a planet with an 8-hour period, there are only 
5–6 strong harmonics, making the FT method reasonably effective. We also found it to 
have some practical advantages: it is fast and easy to compute, and it performs well in 
the presence of the most common types of stellar variability.

By early March of 2013, one of us (S.A.R.) had inspected the FTs of about 10,000 
Kepler light curves. Planet candidates were identified based on the presence of 5 or 
6 strong harmonics. In many cases, periodic fading events turn out to be caused by
eclipsing binary stars, rather than transiting planets. Sometimes these “false positives” could be recognized from the presence of subharmonics, produced by alternating eclipse depths. The resulting list of 93 candidates with strong harmonics and no subharmonics were then vetted in the usual ways \[22, 23\]. We produced a phase-folded light curve after filtering out any stellar variability, and confirmed that there was no detectable alternation in eclipse depths, no detectable ellipsoidal light variations, and no detectable motion of the center of light in the Kepler images that would have suggested a blend between an eclipsing binary and a brighter foreground star.

We realized on March 7 that KIC 8435766 was special. It earned one of the only two “A+” grades that were awarded during the visual inspection\[2\]; it had the brightest host star \(m_{\text{Kep}} = 11.5\) mag; and it showed evidence for tiny dips in between eclipses that were consistent with planetary occultations. It was an unexpected gift. We thought the brightest Kepler stars had already been thoroughly picked over by other groups. After a few days of further analysis, we contacted David Latham to request spectroscopy, and by the beginning of April we could rule out radial-velocity variations at the 100 m s\(^{-1}\) level, placing the mass of the transiting companion within the planetary regime. Our paper was submitted on May 15, 2013. Soon after, on July 12, the system was designated Kepler-78 by the staff at the NASA Exoplanet Archive\[3\].

The spectra obtained by Latham’s group confirmed that the host star was a late G dwarf and suggested it might be suitable for precise Doppler monitoring. The possibility beckoned of measuring the mass of a nearly Earth-sized planet. On May 20 and 21, a conference was held at the Harvard-Smithsonian Center for Astrophysics in honor of Latham’s distinguished career. During a lunch break we met with members of the California Planet Search (CPS) to discuss the possibility of using the Keck I 10 m telescope and the HIRES spectrograph to measure the mass of the planet. During the same meeting, unbeknownst to us, the members of the HARPS-North consortium were also planning to conduct precise Doppler observations at the nearest possible opportunity. Given the brightness of the star and the high level of confidence in the planetary nature of Kepler-78b, it was not too surprising that two different teams embarked on campaigns to measure the mass of the planet.

Both teams began collecting data. It soon became clear that the biggest hurdle in measuring the mass of Kepler-78b would be the starspot activity of the host star. The Kepler data showed fluctuations in total light of 1%, presumably due to starspots rotating across the star’s visible hemisphere. This level of activity leads to spurious Doppler shifts on the order of 10 m s\(^{-1}\), much larger than the expected planetary signal of 1–2 m s\(^{-1}\). Fortunately, the rotation period (12.5 days) is much longer than the orbital period (0.36 day), allowing a clear separation of timescales. It proved possible to detect the planet-induced radial-velocity signal through intensive observations on individual nights, during which the effects of stellar rotation are minimal.

By early June, the CPS and HARPS-N teams had learned of each other’s plans.

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\[2\] The other A+ grade went to KOI-1843.03, which we later learned had already been reported in the literature\[16\].

\[3\] Although it appears in the published paper as “Kepler-XX” because we forgot to inform the \textit{ApJ} editorial staff of the name change before it was too late.
An arrangement was made to submit our journal articles at the same time, but without sharing any results until just beforehand. The two independent results for the planet mass agreed to within 1-σ, despite the different approaches that were taken to cope with the effects of stellar activity. The articles were submitted on September 25, 2013 [24, 25]. Since then, other groups have confirmed the robustness of these measurements by combining both datasets and using different analysis techniques [26, 27]. The most recent such study found $R_p = 1.20 \pm 0.09 \, R_\oplus$ and $M_p = 1.87 \pm 0.27 \, M_\oplus$, giving a mean density of $6.0^{+1.9}_{-1.4} \, \frac{\text{g}}{\text{cm}^3}$ [27]. This is consistent with the Earth’s mean density of 5.5 g cm$^{-3}$, although the uncertainty is large enough to allow for a wide range of possible combinations. Using a simple model consisting only of rock and iron, the iron fraction is constrained to be 0.32 ± 0.16.

![Figure 2: Transit light curve of Kepler-78b](image)

The brightness of the host star has enabled other interesting measurements. Any long-term change in orbital period due to tidal effects, planet-planet interactions, or other reasons must satisfy $|\dot{P}/P| > 2.8 \, \text{Myr}$. The detection of occultations and the planet’s “phase curve” (the gradual light variations that are seen with the same period as the planetary orbit) help to limit the possibilities for the planet’s visual albedo and surface temperature. If the Bond albedo is 0.5, the dayside temperature must be $\approx 2600 \, \text{K}$, while if the albedo is very small then the temperature could be as high as...
3000 K. The nightside temperature is less than 2700 K (3-σ). Future observations at multiple wavelengths, perhaps with the James Webb Space Telescope, will lead to better constraints.

The relatively young age of the star (750 Myr) and high level of activity have allowed some investigators to characterize the stellar magnetic field. Spectropolarimetry was used to infer a surface magnetic field strength of 16 G for the host star, by exploiting the Zeeman effect [29]. It has been suggested that planet-star interactions could lead to a detectable modulation in magnetic activity through a mechanism similar to the electrodynamic coupling between Jupiter and Io [30]. No such modulation has yet been detected.

3. The USP planet population
3.1. Physical characteristics

Having indulged ourselves in telling the story of Kepler-78, we turn to the more scientifically relevant task of summarizing what has been learned about USP planets in general. To get oriented, we begin with some basic physical considerations. We also allude to some of the more sophisticated models that have been developed for extremely hot rocky planets, in response to the discoveries of Corot-7b, Kepler-10b, 55 Cnc e, and Kepler-78b.

To set the scale of the orbit, we apply Kepler’s third law,

\[ a = \text{0.0196 AU} \left( \frac{P_{\text{orb}}}{1 \text{ day}} \right)^{2/3} \left( \frac{M_\star}{M_{\odot}} \right)^{1/3}, \quad a = \text{4.2} \left( \frac{P_{\text{orb}}}{1 \text{ day}} \right)^{2/3} \left( \frac{\rho_\star}{\rho_{\odot}} \right)^{1/3}. \] (3)

For these fiducial parameters, the angular diameter of the star in the sky of the planet is 27°, i.e., fifty times wider than the Sun in our sky.

At this short range, tidal interactions lead to relatively rapid orbital and spin evolution. In the constant-lag-angle model of the equilibrium tide, the timescale for orbital circularization is [31, 32]

\[ \frac{\dot{e}}{\dot{e}^*} \sim 1.7 \text{ Myr} \left( \frac{Q'_p}{10^7} \right) \left( \frac{M_\star}{M_\odot} \right) \left( \frac{R_\star}{R_{\odot}} \right)^5 \left( \frac{\rho_\star}{\rho_{\odot}} \right)^{5/3} \left( \frac{P_{\text{orb}}}{1 \text{ day}} \right)^{13/3}, \] (4)

where \( Q'_p \) is the modified tidal quality factor characterizing the dissipation rate of tidal oscillations, scaled to a customary value for the Earth. The timescale for the planet to achieve spin-orbit synchrony is even shorter, by a factor on the order of \( (R_p/a)^2 \). Therefore when we see a USP planet around a mature main-sequence star it reasonable to assume (until proven otherwise) that the planet has a circular orbit and a permanent dayside and nightside. However, the orbit of a terrestrial-mass USP planet does not have enough angular momentum to spin up the star and achieve a stable double-synchronous state. Instead, the planet spirals into the star on a timescale [31, 32]

\[ \frac{P}{\dot{P}} \sim 30 \text{ Gyr} \left( \frac{Q'_p}{10^6} \right) \left( \frac{M_\star}{M_\odot} \right) \left( \frac{P_{\text{orb}}}{1 \text{ day}} \right)^{13/3} \left( \frac{\rho_\star}{\rho_{\odot}} \right)^{5/3}, \] (5)
where $Q'_\star$ is the star’s modified tidal quality parameter. Since $Q'_\star$ is uncertain by at least an order of magnitude, it is not clear whether tidal orbital decay is important on astrophysical timescales.

A one-day planet around a Sun-like star intercepts a flux of $3.5 \text{ MW m}^{-2}$, about 2600 times the flux of the Sun impinging on the Earth. Under the simplifying assumption that all the incident energy is re-radiated locally, the planet’s surface at the substellar point (high noon) is raised to a temperature of 2800 K. This is not far from the temperature of the glowing tungsten filament in an incandescent light [15]. It is also hot enough to melt silicates and iron, a fact which has led to theoretical work on the properties of the resulting lava oceans [13, 33, 34] and mantle convection [35, 36].

During the first $10^7$ years of a star’s active youth, a USP planet would be bathed in ultraviolet and X-ray radiation. The gas near the XUV photosphere would be heated to such a degree that the pressure gradient would drive a hydrodynamic wind, leading to atmospheric escape [37, 38, 39]. This would lead to a complete loss of any hydrogen-helium atmosphere. Unless the planet has an envelope of water vapor or other elements heavy enough to be retained [40], the bare solid surface would sit beneath a very thin atmosphere with a maximum pressure of order $10^{-5}$ atm [15]. Models which track the chemistry of Earth’s crust as it is heated to a temperature of 1500–3000 K suggest that the outgassed atmosphere would be mainly composed of Na, O$_2$, O, and SiO [41].

3.2. Detections

Several groups have undertaken systematic searches of the Kepler data for short-period planets, only a few of which were specifically designed for periods shorter than about one day. In 2014, we and our collaborators published a list of 106 USP planet candidates based on the concatenation of our own detections as well as those of other groups [16, 1, 42]. The characteristics of the stars and planets were later clarified based on high-resolution optical spectroscopy, and a few false positives were uncovered [43].

In 2016, the population of USP planets was noted by other investigators. One group confirmed that the sample of strongly irradiated planets does not include many with sizes exceeding $2 R_\oplus$ [44]. Their sample consisted of Kepler systems for which we have unusually good knowledge of the stellar and planetary sizes, thanks to the detection of asteroseismic oscillations. Another study concluded that at least 17% of the “hot Earths” detected by Kepler have a different radius/period distribution than the planets in the collection of Kepler multi-planet systems [45].

In addition, over the last few years, a fresh sample of USP planets has been found using data from the ongoing NASA K2 mission. A systematic search was undertaken by the Short Period Planets Group [46], resulting in 19 candidates. Other groups have validated and characterized about a dozen additional candidates [47, 48, 49, 50, 51, 19].

3.3. Occurrence rate

About one out of 200 Sun-like stars (G dwarfs) has an ultra-short-period planet. This result is based on a systematic and largely automated search of the Kepler data using our FT pipeline, calibrated with inject-and-recover simulations [2]. The simulations showed that the efficiency of detecting planets larger than $2 R_\oplus$ was higher than 90%, and that it dropped below 50% for planets smaller than $1 R_\oplus$. After correcting for
this sensitivity function, and for the transit probabilities, the occurrence rate was found to be \((0.51 \pm 0.07)\%\) for planets larger than \(0.84 R_{\oplus}\) and periods shorter than one day.

Among the other results of this survey was evidence for a strong dependence of the occurrence rate upon the mass of the host star. The measured occurrence rate falls from \((1.1 \pm 0.4)\%\) for M dwarfs to \((0.15 \pm 0.05)\%\) for F dwarfs. There are still substantial uncertainties in the occurrence rates for stars at either end of this range, due to the relatively small number of detections. It is perhaps telling, though, that most of the USP planets found with \(K2\) data are around K and M dwarfs.

![Figure 3: Occurrence rates as a function of period and radius for USP planets orbiting G and K dwarfs][2]. The period distribution is consistent with a power law. The radius distribution shows a sharp decline at around \(2 R_{\oplus}\).

3.4. Period and radius distributions

Figure 3 shows the inferred radius and period distribution of USP planets based on our FT survey, after accounting for the survey completeness. As we consider periods shrinking from 24 to 4 hours, the occurrence rate falls by more than an order of magnitude. The trend with period is compatible with an extrapolation of the trend that had been noted previously for periods between 1 and 10 days [54, 55]. This is illustrated in Figure 4. Likewise, the occurrence rate of planets larger than \(2 R_{\oplus}\) is at least a factor of five smaller than the rate of Earth-sized planets. This, too, is compatible with a more general trend: the radius distribution of all planets with periods shorter than 100 days shows a dip in occurrence between 1.5 and \(2 R_{\oplus}\) [56].

This dip has been attributed to photo-evaporation [57]. In this interpretation, close-in planets begin their existence as rocky bodies of approximately \(3 M_{\oplus}\) which accrete differing amounts of hydrogen and helium gas from the surrounding protoplanetary disk. Those that accrete only a little gas — less than a few per cent of the total planet
mass — lose it all during the $10^7$ years of high-energy irradiation by the young and magnetically active star. Such planets are observed today as rocky bodies with sizes smaller than $1.5 R_\oplus$. Most of the USP planets seem to be in this category. If instead a higher mass of gas is accreted, a substantial fraction is still left over by the time the star quiets down and loses its evaporative effect. Such an atmosphere, even when its mass is on the order of only a per cent of the total mass, has such a large scale height that it increases the planet’s effective size by a factor of two. We observe these planets today to be swollen to sizes of $2–3 R_\oplus$. Such planets are commonly seen with orbital periods from a few to 100 days, but as we have stated above, they are rarely seen as USP planets.

3.5. Masses

An important part of the Kepler-78 story was the feasibility of Doppler mass measurement. There are several reasons why the USP planets are attractive targets for Doppler monitoring. The radial-velocity amplitude scales as $P^{-1/3}$ and is therefore higher for shorter-period planets. A full orbit can be sampled in just a few nights, or even a single night. The Doppler signal is insulated from the effects of stellar variability to some degree, because the orbital period is usually much shorter than the stellar rotation period. Still, because the planets tend to be small, the Doppler signals have amplitudes of only a few meters per second, making them challenging to detect. Masses have been measured for ten USP planets (see Figure 5). On the whole, the USP planets seem consistent with an Earth-like composition of 70% rock and 30% iron.
K2-229b has a higher density suggesting a more massive iron core. WASP-47e and 55 Cnc e have a lower density and are compatible with pure rock, or a rocky-iron body surrounded by a layer of water (or other volatiles).

At the very shortest periods, a constraint on the planet’s composition can be obtained even without any Doppler data. The mere requirement that the planet is outside of the Roche limit — that it has not been ripped apart by the star’s tidal gravitational force — gives a lower bound on the planet’s mean density. An approximate expression for the Roche-limiting orbital period is

\[
P_{\text{min}} \approx 12.6 \, \text{hr} \left( \frac{\langle \rho \rangle}{1 \, \text{g cm}^{-3}} \right)^{-1/2} \left( \frac{\rho_c}{\langle \rho \rangle} \right)^{-0.16},\]

where \( \langle \rho \rangle \) and \( \rho_c \) are the planet’s mean and central density, respectively. This formula is derived from the classical expression for the Roche limit of an incompressible fluid body, along with a correction for compressibility (the second factor) based on polytrope models. It has been applied to two planets, KOI-1843.03 (\( P_{\text{orb}} = 4.2 \) hours) and K2-137b (4.3 hours), to argue that they probably have large iron cores [17, 19]. We note, however, that the leading coefficient in Eqn. (6) could be substantially lower, depending on the roles of material strength and friction, and whether the body actually splits apart once the Roche limit is violated [58, 59]. More theoretical work is warranted before we can have confidence in constraints on planet compositions based on the Roche limit.

### 3.6. Occultations

When a planet’s orbit carries it behind its host star and out of view, the total system flux decreases by an amount proportional to the average brightness of the planet’s dayside. As noted earlier, Kepler-78b is the smallest planet for which it has been possible to detect the loss of light during planetary occultations. The next smallest such planet is K2-141b [51], which has a size of 1.5 \( R_\oplus \) and an orbital period of 6.7 hours. In both cases the detection was based on white-light observations with the *Kepler* telescope. In neither case has it been possible to determine what fraction of the dayside flux arises from reflected light, as opposed to reprocessed light (thermal emission). This would require data obtained over a wider range of wavelengths.

Another USP planet for which occultations have been detected is 55 Cnc e (1.9 \( R_\oplus \), \( P = 17.7 \) hours). In this case, the detections were made with the *Spitzer* space telescope at a wavelength of 4.5 \( \mu \text{m} \), far enough into the infrared range of the spectrum that the signal is probably dominated by thermal emission [69]. The measurement was repeated eight times, and the results for the brightness temperature ranged from 1300–2800 K [63]. The minimum and maximum amplitudes of the observed occultation signal were found to differ by 3.3-sigma. If this apparent variability represents genuine fluctuations of the brightness of the planet’s dayside, the observers suggested they could be caused by widespread volcanic activity. The observed variations in flux over the course of the entire orbit, when attributed to the changing planetary phase, imply dayside and nightside temperatures of 2700 ± 270 K and 1380 ± 400 K, respectively [70].

### 3.7. Metallicity

Giant planets with periods shorter than a few years, including hot Jupiters, have long been known to be more common around stars of high metallicity. A recent *Kepler*
study concluded that the occurrence of hot Jupiters rises with the 3rd or 4th power of the metal abundance \[71\]. The USP planets are also associated with higher-than-average metallicity, but the dependence is not as strong as for the hot Jupiters \[43\]. In this respect, the USP planets are similar to the broader sample of Kepler planets with periods shorter than 10 days \[72\] \[71\] \[73\].

The lack of strong association between high metallicity and the occurrence of USP planets was of particular interest because it had been postulated that hot Jupiters are the progenitors of USP planets \[1\] \[74\] \[75\]. In this scenario, the USP planets are the bare rocky cores of giant planets that approached the star too closely and lost their gas, due to photo-evaporation, Roche lobe overflow, or some other process. However, in this scenario, one would expect the host stars of hot Jupiters and USP planets to have similar characteristics, including metallicity. Since this is not the case \[43\], it seems unlikely that hot Jupiters are the progenitors of USP planets. This still leaves open the possibility that the progenitors are gas-ensheathed planets of only a few Earth masses, as discussed in Section 3.4.
3.8. Longer period companions

Another difference between hot Jupiters and USP planets is in their tendency to have nearby planetary companions. Hot Jupiters are rarely found with other planets within a factor of 2–3 in orbital period or distance [86]. In contrast, USP planets are almost always associated with longer-period planetary companions [2, 80]. This conclusion is partly based on the numerous detections of longer-period transiting planets in systems that have a USP planet (see Figure 6). It is also based on a statistical argument involving the decrease in transit probability with orbital period: many of the Kepler stars for which only the transits of a USP planet are detected must be multi-planet systems for which the outer planet does not happen to be transiting [2].

One exceptional system is WASP-47, which has a hot Jupiter and a USP planet [84]. There is also a third planet orbiting just outside of the orbit of the hot Jupiter. This system seems too dynamically fragile for the hot Jupiter to have undergone high-eccentricity migration, a scenario that is often invoked to explain how a giant planet could find its way into such a tight orbit. A similar system is Kepler-487, which has a
USP planet and a “warm Jupiter” with a period of 15.4 days, in addition to two other transiting planets [77]. This system has not yet been as well characterized as WASP-47.

The multi-planet systems that include a USP planet differ from the other Kepler multi-planet systems in an intriguing way. A typical system without a USP planet has a ratio of between 1.5 and 4 between the periods of the outer and inner planets of an adjacent pair [87]. But when the inner planet has a period shorter than one day, the period ratio is almost always greater than 3 [88], as illustrated in Figure 5. This suggests that some process has widened the period ratio. Perhaps the period of the USP planet has shrunk due to tidal orbital decay that is either ongoing, or that took place early in the system’s history when the star had still not contracted onto the main sequence and would have been more susceptible to tides.

The same systems that show wider-than-usual period ratios also appear to have higher mutual inclinations. This is based on comparisons between the transit impact parameters of planets in the same system, which gives a lower limit on mutual inclination. Among the Kepler multi-planet systems for which the innermost planet has \( a/R_\odot < 5 \), the mutual inclination distribution ranges up to 10-15 degrees [89, 90]. This is higher than the 2-5 degrees that have generally been found for pairs of planets in wider orbits [87]. This finding suggests that USP planets have experienced inclination excitation in addition to orbital shrinkage.

3.9. Formation theories

Before describing some of the theories for the formation of USP planets, it is time for another reminder that there is no sharp astrophysical distinction between the “ultra-short-period” planets with periods of less than one day and the merely “short-period” planets with periods of 1–10 days. The problems related to the formation of short-period planets have been with us since 1995, and we will not attempt a comprehensive review here. Instead we make note of some of the work relating specifically to the planets with the very shortest orbital periods.

Even before the discovery of Corot-7b, Raymond et al. enumerated six possible formation pathways for “hot Earths” [91]. As summarized below, these pathways lead to different predictions for the final compositions for the USP planets, and for the properties of any additional planets around the same star. In light of the knowledge we have gained over the last 10 years, we can try to fill in the score card:

1. Accretion from solid material in the innermost part of the protoplanetary disk. This “in situ” accretion process would typically lead to several hot Earths spaced by 20–60 mutual Hill radii. Such systems have indeed been observed. This formation pathway would also result in a dry composition (0.1–1% water), which is consistent with the existing mass and radius measurements.

2. Spiraling-in of a planet from beyond the ice line, due to gravitational interactions with the disk (Type I migration). This would likely lead to resonant chains of multiple planets. Such resonant chains are infrequent in the Kepler sample, and to our knowledge there is are no examples involving a USP planet. This scenario would also lead to water-rich planets, with 10% or more of their mass in water. The observations are not yet good enough to try and confirm or rule out a water fraction of 10%.
3. Accretion of material that is locked in mean-motion resonance with a migrating giant planet and thereby “shepherded” inward. This would lead to systems in which the USP planet is parked next to a giant planet. The only known systems that fit this description are WASP-47 and Kepler-487.

4. Accretion of material shepherded by sweeping secular resonances. In this scenario, there are at least two giant planets. The resonance is between the precession rate induced by the other planet, and that induced by the (gradually disappearing) disk. This would lead to systems in which hot Earths and two giant planets coexist, which have not been observed.

5. Eccentricity excitation followed by tidal circularization of an initially wide-orbiting planet. This would result in isolated USP planets. In reality, there are many USP planets with known companions (see Fig. 6), and statistical arguments suggest that the majority of USPs are part of compact multi-planet systems [28, 80].

6. Photo-evaporation of a formerly gaseous planet that approached the star too closely. As noted earlier, this scenario was later elaborated to predict a gap in the radius distribution of close-in planets — or a “valley” in the space of radius and period — which has been observed. Of course, this theory by itself does not explain where the progenitor planet came from.

Obviously the picture is not yet clear, nor is it clear that these six pathways are the only possibilities. Nevertheless, it does seem that elements of the in situ and photo-evaporation theories have withstood a decade of observations. In recent years, a few more specific theories have been offered:

1. Schlaufman et al. proposed that a planet can be driven to short periods by dynamical interactions with nearby planets in wider orbits, at which point tidal interactions with the stars shrink the orbit still further, forming an ultra-short-period planet [92]. They predicted that USP planets should be more common around massive (F-type) stars than around lower-mass stars, because massive stars should have weaker tidal dissipation. This appears to be the opposite of what is observed; in our survey, the occurrence was lowest for the F dwarfs and highest for M dwarfs.

2. Lee & Chiang agreed that tidal dissipation is responsible for shrinking the orbits, but proposed a different initial condition: the planet forms from material that collects near the innermost edge of the protoplanetary disk [55]. The location of the inner edge is the distance at which the orbital period matched the stellar rotation period at early times, which is 10 days for Sun-like stars. In this way, they explain why the occurrence rate of planets begins dropping for periods less than 10 days. In their theory, the USP planets are gradually spiraling inward due to tidal orbital decay. They predict that for more massive and rapidly rotating A stars, the break in the period distribution of close-in rocky planets (should they exist) will occur closer to one day.

3. Petrovich et al. investigated the possibility of eccentricity excitation from secular dynamical chaos in compact multiplanet systems [93]. They predicted that USP planets would often be accompanied by outer planets extending out to 1 AU. They also predicted that USP planets would show a broad range of inclinations
with respect to the equator of the host star, and mutual inclinations with respect to the orbits of outer planets. This latter prediction, at least, has found empirical support [90].

4. Other ultra-short-period phenomena

4.1. Giant planets

There are 6 known examples of giant planets \( (R_p > 8R_\oplus) \) with a period shorter than one day. These rare butterflies are WASP-18b, WASP-43b, WASP-103b, HATS-18b, KELT-16b, and WASP-19b, the last of which has the shortest known period of 0.788 days [94]. None of them were found in the \textit{Kepler} survey; rather, they were found in ground-based transit surveys that were capable of searching a larger sample of stars. Their occurrence must be lower by at least an order of magnitude than that of terrestrial-sized USP planets. Because of the large masses of these planets, they are valuable for testing theories of gravitational tidal interactions. As described above and in Section 3.1, tides should cause the star to spin faster and the orbit to shrink, ultimately leading to the engulfment of the planet. However, tidal theory makes no firm prediction for the timescale over which the orbit decays. The timescale depends not only on the planet mass and orbital distance, but also on the rate of tidal dissipation within the star, which is uncertain by at least an order of magnitude. If we could observe the steady shrinkage of the orbital period of a hot Jupiter, we would be able to confirm a fundamental theoretical prediction and clarify the rate of tidal dissipation within Sun-like stars, a longstanding uncertainty in stellar astrophysics. So far, the best candidate for period decay is WASP-12 [95, 92].

4.2. Pseudoplanets

The T Tauri star PTFO 8-8695, less than a few million years old, exhibits periodic fading events that were interpreted as the transits of a giant planet on a precessing orbit [96, 97, 98]. This discovery was greeted with great interest, because the study of hot Jupiters around very young stars would provide information about the timing of planet formation, the structure of newborn planets still cooling and contracting, and the mechanism for shrinking planetary orbits and creating hot Jupiters. However, follow-up observations revealed some problems with the planet hypothesis: the “transits” are not strictly periodic, the shape of the light curve varies substantially with wavelength and orbital cycle, and an occultation signal with the expected amplitude has been ruled out [99]. The origin of the fading events is still unknown, though, and some investigators are still pursuing the planet hypothesis [100].

Another case of questionable USP planets is KIC 05807616, a hot B subdwarf that showed evidence for two planets with orbital periods 5.8 and 8.2 hours. The evidence was based on the observed periodic modulations in the light from the system, which were consistent with the illumination variations of the putative planets [101]. However, additional data showed that these periodic variations were not coherent enough to arise from orbital motion [102]. Again, the true origin of these planet-like signals has not been ascertained.
4.3. Disintegrating planets

Another discovery that emerged from the Fourier-based search of the Kepler data was the first of a small subset of objects referred to as “disintegrating” planets. The objects are KIC 12557548b (KIC 1255b for short), KOI-2700b, and K2-22b, with orbital periods of 15.7, 22, and 9.5 hours, respectively [103, 104, 105, 106]. In all three cases, the transit signal is asymmetric around the time of minimum light, and there are variations in the transit depth. KIC 1255b and KOI-2700b have much longer egress times than ingress times, while KIC 1255b and K2-22b exhibit highly variable depths, often from one transit to the next.

These characteristics strongly suggest that the occulter is an elongated tail of dusty material streaming away from a hot rocky planet. It is important to note that the transits in these objects do not reveal any evidence of the underlying solid body itself. For two of the objects the transit depths are on the order of 0.5%, implying an obscuring area comparable to that of Jupiter, but the obscuration is presumed to be almost entirely due to dust extinction. In all three cases the upper limits on the size of the solid body itself is on the order of the size of the Earth, and theoretical considerations suggest the true sizes may be comparable to that of the Moon [107].

The shape of the dust tail is largely dictated by radiation pressure forces. The likely result is a trailing dust tail unless the radiation pressure forces are small, which can occur for either very large (\(\gtrsim 10\mu m\)) or tiny dust particles (\(\lesssim 0.1\mu m\)). The inferred mass-loss rates from the planets are based on the amount of dust required to yield such significant extinction of the host star, and are in the range of \(10^{10} - 10^{11}\) g s\(^{-1}\). This is roughly equivalent to a few lunar masses per Gyr. These and other properties have been recently reviewed by Van Lieshout & Rappaport [106].

4.4. Disintegrating asteroids

WD 1145+017 is a unique object thought to be a white dwarf with a set of disintegrating asteroids in ultra-short-period orbits [108]. The system exhibits transits with multiple periods in the range from 4.5 to 4.9 hours. It is believed that the asteroids are responsible for dust clouds which then produce the transits. These transits can be as deep as 60% and last anywhere from about 10 minutes to an hour. All the bodies that have been inferred are orbiting the white dwarf at a distance of only one stellar radius. Given the stellar luminosity of 0.1 \(L_{\odot}\), the equilibrium temperatures of the dust grains are about 1000–2000 K, depending on their size and composition [109]. We are likely witnessing the disintegration of planetary bodies that survived the metamorphosis of the host star from a dwarf into a giant and then into a white dwarf.

4.5. Unknown unknowns

The disintegrating planets and asteroids are examples of new and interesting phenomena that were discovered by sifting through Kepler data. The next few years will bring another good opportunity for a comprehensive exploration of ultra-short-period phenomena. The Transiting Exoplanet Survey Satellite (TESS), launched in April 2018, is performing time-series photometry over about 90% of the sky using four 10 cm telescopes [110]. Stars are observed for a duration ranging from one month to one year, depending on ecliptic latitude.
With TESS data, we will be able to find USP planets around stars that are several magnitudes brighter than typical Kepler stars. This will provide more targets that are suitable for precise Doppler mass measurements. With a sample of brighter stars, it will also be easier to test for compositional similarities between stars with USP planets and stars with other types of planets that might be the progenitors of USP planets.

More generally, the TESS data will be another giant haystack within which to search for interesting needles: planets in unusual configurations, disintegrating planets and asteroids, and hitherto unknown phenomena. Searches for USP planets may reveal the hypothesized “iron planets” that could be formed when rocky planets are battered by giant impacts, vaporizing the rocky mantle but leaving the iron core intact. TESS will also be able to search for hot Jupiters within a sample of stars that is orders of magnitude larger than the Kepler sample, perhaps allowing us to find planets undergoing rapid orbital decay. Although TESS attracts the most attention for its potential to find potentially habitable planets around red dwarf stars, the mission can also be regarded as a search for rare short-period phenomena over a wider range of stellar masses and ages than has been explored before.

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References
[5] B. S. Gaudi, S. Seager, G. Mallen-Ornelas, On the Period Distribution of Close-in Extrasolar Giant Planets, ApJ623 (2005) 472–481. arXiv:astro-ph/0409443, doi:10.1086/428478.

[6] J. Pepper, A. Gould, D. L. Depoy, Using All-Sky Surveys to Find Planetary Transits, AcA53 (2003) 213–228. arXiv:astro-ph/0208042.

[7] K. C. Sahu, S. Casertano, H. E. Bond, J. Valenti, T. Ed Smith, D. Minniti, M. Zoccali, M. Livio, N. Panagia, N. Piskunov, T. M. Brown, T. Brown, A. Renzini, R. M. Rich, W. Clarkson, S. Lubow. Transiting extrasolar planetary candidates in the Galactic bulge, Nature443 (2006) 534–540. arXiv:astro-ph/0610098, doi:10.1038/nature05158.

[8] A. Léger, D. Rouan, J. Schneider, P. Barge, M. Fridlund, B. Samuel, M. Olivier, E. Guenther, M. Deleuil, H. J. Deeg, M. Auvéргne, R. Alonso, S. Aigrain, A. Alapini, J. M. Almenara, A. Baglin, M. Barbieri, H. Bruntt, P. Bordé, F. Bouchy, J. Cabrera, C. Catala, L. Carone, S. Carpano, S. Csizmadia, R. Dvorák, A. Erikson, S. Ferraz-Mello, B. Foing, F. Fressin, D. Gandolfi, M. Gillon, P. Gondoin, O. Grassett, T. Guillot, A. Hatszeg, G. Hébrard, L. Jordà, H. Lammer, A. Llebaria, B. Loeillet, M. Mayor, T. Mazeh, C. Moutou, M. Pätzold, F. Pont, D. Queloz, H. Rauer, S. Renner, R. Samadi, A. Shporer, C. Sotin, B. Tingley, G. Wuchterl, M. Adda, P. Agogu, T. Appourchaux, H. Ballans, P. Baron, T. Beaufort, R. Bellenger, R. Berlin, P. Bernardi, D. Blouin, F. Baudin, P. Bodin, L. Boisnard, L. Boit, F. Bonneau, S. Borzeix, R. Briet, J.-T. Buey, B. Butler, D. Cailleau, R. Cautain, P.-Y. Chabaud, S. Chaintreuil, F. Chiavassa, V. Costes, V. Cuna Parrho, F. de Oliveira Fialho, M. Decaudin, J.-M. Defise, S. Djalal, G. Epstein, G.-E. Exil, C. Fauré, T. Fenouillet, A. Gaboriaud, A. Gallic, P. Gaumet, P. Gavalda, E. Grollier, R. Grunet, L. Gueguen, V. Guis, V. Guivarc’h, P. Guterman, D. Hallouard, J. Hasiba, F. Heuripeau, G. Hunzinger, H. Hustaix, C. Imad, C. Imbert, B. Johlander, M. Jouret, P. Journoud, F. Karioty, L. Kerjean, C. Lafaille, L. Lafond, T. Lam-Trong, P. Landiech, V. Lapeyre, T. Larqué, P. Lauter, N. Lautier, H. Lecanu, L. Lefevre, B. Lepuyet, P. Levacher, A. Magnan, E. Mazy, F. Mertens, J.-M. Messner, J.-C. Meunier, J.-P. Michel, W. Monjoins, D. Naudet, K. Nguyen-Kim, J.-L. Orcesi, H. Oottner, R. Perez, G. Peter, P. Plasson, J.-Y. Plessier, B. Pontet, A. Pradines, C. Quentin, J.-L. Reynaud, G. Rolland, P. Rillonhagen, R. Romagnan, N. Russ, R. Schmidt, N. Schwartz, I. Sebbag, G. Sedes, H. Smit, M. B. Steller, W. Sunter, C. Surace, M. Tello, D. Tiphène, P. Toulouse, B. Ulmer, O. Vandermeur, E. Vergnault, A. Vissel, P. Zanatta, Transiting exoplanets from the CoRoT space mission. VIII. CoRoT-7b: the first super-Earth with measured radius, A&A506 (2009) 287–302. arXiv:0908.0241, doi:10.1051/0004-6361/200911933.

[9] N. M. Batalha, W. J. Borucki, S. T. Bryson, L. A. Buchhave, D. A. Caldwell, J. Christensen-Dalsgaard, D. Ciardi, E. W. Dunham, F. Fressin, T. N. Gautier, III, R. L. Gilliland, M. R. Haas, S. B. Howell, J. M. Jenkins, H. Kjeldsen, D. G. Koch, D. W. Latham, J. J. Lissauer, G. W. Marcy, J. F. Rowe, D. D. Sasselov, S. Seager, J. H. Steffen, G. Torres, G. S. Basri, T. M. Brown, D. Charbonneau,
J. Christiansen, B. Clarke, W. D. Cochran, A. Dupree, D. C. Fabrycky, D. Fischer, E. B. Ford, J. Fortney, F. R. Girouard, M. J. Holman, J. Johnson, H. Isaacson, T. C. Klaus, P. Machalek, A. V. Moorehead, R. C. Morehead, D. Ragozzine, P. Tenenbaum, J. Twicken, S. Quinn, J. VanCleve, L. M. Walkowicz, W. F. Welsh, E. Devore, A. Gould, Kepler’s First Rocky Planet: Kepler-10b, ApJ729 (2011) 27. arXiv:1102.0605 doi:10.1088/0004-637X/729/1/27

[10] B. E. McArthur, M. Endl, W. D. Cochran, G. F. Benedict, D. A. Fischer, G. W. Marcy, R. P. Butler, D. Naef, M. Mayor, D. Queloz, S. Udry, T. E. Harrison, Detection of a Neptune-Mass Planet in the $\rho$ i Cancri System Using the Hobby-Eberly Telescope, ApJL614 (2004) L81–L84. arXiv:astro-ph/0408585 doi:10.1086/425561

[11] D. A. Fischer, G. W. Marcy, R. P. Butler, S. S. Vogt, G. Laughlin, G. W. Henry, D. Abouav, K. M. G. Peek, J. T. Wright, J. A. Johnson, C. McCarthy, H. Isaacson, Five Planets Orbiting 55 Cancri, ApJ675 (2008) 790–801. arXiv:0712.3917 doi:10.1086/525561

[12] R. I. Dawson, D. C. Fabrycky, Radial Velocity Planets De-aliased: A New, Short Period for Super-Earth 55 Cnc e, ApJ722 (2010) 937–953. arXiv:1005.4050 doi:10.1088/0004-637X/722/1/937

[13] J. N. Winn, J. M. Matthews, R. I. Dawson, D. Fabrycky, M. J. Holman, T. Kallinger, R. Kuschnig, D. Sasselov, D. Dragomir, D. B. Guenther, A. F. J. Moffat, J. F. Rowe, S. Rucinski, W. W. Weiss, A Super-Earth Transiting a Naked-eye Star, ApJL737 (2011) L18. arXiv:1104.5230 doi:10.1088/2041-8205/737/1/L18

[14] B.-O. Demory, M. Gillon, D. Deming, D. Valencia, S. Seager, B. Benneke, C. Lovis, P. Cubillos, J. Harrington, K. B. Stevenson, M. Mayor, F. Pepe, D. Queloz, D. Ségransan, S. Udry, Detection of a transit of the super-Earth 55 Cancri e with warm Spitzer, A&A533 (2011) A114. arXiv:1105.0415 doi:10.1051/0004-6361/201117178

[15] A. Léger, O. Grasset, B. Fegley, F. Codron, A. F. Albarede, P. Barge, R. Barnes, P. Cané, S. Carpy, F. Catalano, C. Cavarroc, O. Demangeon, S. Ferraz-Mello, P. Gabor, J.-M. Grießmeier, J. Leibacher, G. Libourel, A.-S. Maurin, S. N. Raymond, D. Rouan, B. Samuel, L. Schaefer, J. Schneider, P. A. Schuller, F. Selcis, C. Sotin, The extreme physical properties of the CoRoT-7b super-Earth, Icarus213 (2011) 1–11. arXiv:1102.1629 doi:10.1016/j.icarus.2011.02.004

[16] A. Ofir, S. Dreizler, An independent planet search in the Kepler dataset. I. One hundred new candidates and revised Kepler objects of interest, A&A555 (2013) A58. arXiv:1206.5347 doi:10.1051/0004-6361/201219877

[17] S. Rappaport, R. Sanchis-Ojeda, L. A. Rogers, A. Levine, J. N. Winn, The Roche Limit for Close-orbiting Planets: Minimum Density, Composition Constraints,
[18] J. J. Lissauer, G. W. Marcy, J. F. Rowe, S. T. Bryson, E. Adams, L. A. Buchhave, D. R. Ciardi, W. D. Cochran, D. C. Fabrycky, E. B. Ford, F. Fressin, J. Geary, R. L. Gilliland, M. J. Holman, S. B. Howell, J. M. Jenkins, K. Kinemuchi, D. G. Koch, R. C. Morehead, D. Ragozzine, S. E. Seader, P. G. Tanenbaum, G. Torres, J. D. Twicken, Almost All of Kepler’s Multiple-planet Candidates Are Planets, ApJ750 (2012) 112. arXiv:1201.5424 doi:10.1088/0004-637X/750/2/112.

[19] A. M. S. Smith, J. Cabrera, S. Csizmadia, F. Dai, D. Gandolfi, T. Hirano, J. N. Winn, S. Albrecht, R. Alonso, G. Antoniello, O. Barragán, H. Deeg, P. Eigmüller, M. Endl, A. Erikson, M. Fridlund, A. Fukui, S. Grziwa, E. W. Guenther, A. P. Hatzes, D. Hidalgo, A. W. Howard, H. Isaacson, J. Korth, M. Kuzuhara, J. Livingston, N. Narita, D. Nespral, G. Nowak, E. Palle, M. Pätzold, C. M. Persson, E. Petigura, J. Prieto-Arranz, H. Rauer, I. Ribas, V. Van Eylen, K2-137 b: an Earth-sized planet in a 4.3-h orbit around an M-dwarf, MNRAS474 (2018) 5523–5533. arXiv:1707.04549 doi:10.1093/mnras/stx2891.

[20] R. W. Slawson, A. Prša, W. F. Welsh, J. A. Orosz, M. Rucker, N. Batalha, L. R. Doyle, S. G. Engle, K. Conroy, J. Coughlin, T. A. Gregg, T. Fetherolf, D. R. Short, G. Windmiller, D. C. Fabrycky, S. B. Howell, J. M. Jenkins, K. Uddin, F. Mullally, S. E. Seader, S. E. Thompson, D. T. Sanderfer, W. Borucki, D. Koch, Kepler Eclipsing Binary Stars. II. 2165 Eclipsing Binaries in the Second Data Release, AJ142 (2011) 160. arXiv:1103.1659 doi:10.1088/0004-6256/142/5/160.

[21] G. Kovács, S. Zucker, T. Mazeh, A box-fitting algorithm in the search for periodic transits, A&A391 (2002) 369–377. arXiv:astro-ph/0206099 doi:10.1051/0004-6361:20020802.

[22] J. M. Jenkins, D. A. Caldwell, H. Chandrasekaran, J. D. Twicken, S. T. Bryson, E. V. Quintana, B. D. Clarke, J. Li, C. Allen, P. Tenenbaum, H. Wu, T. C. Klaus, J. Van Cleve, J. A. Dotson, M. R. Haas, R. L. Gilliland, D. G. Koch, W. J. Borucki, Initial Characteristics of Kepler Long Cadence Data for Detecting Transiting Planets, ApJL713 (2010) L120–L125. arXiv:1001.0256 doi:10.1088/2041-8205/713/2/L120.

[23] T. D. Morton, J. A. Johnson, On the Low False Positive Probabilities of Kepler Planet Candidates, ApJ738 (2011) 170. arXiv:1101.5630 doi:10.1088/0004-637X/738/2/170.

[24] A. W. Howard, R. Sanchis-Ojeda, G. W. Marcy, J. A. Johnson, J. N. Winn, H. Isaacson, D. A. Fischer, B. J. Fulton, E. Sinukoff, J. J. Fortney, A rocky composition for an Earth-sized exoplanet, Nature503 (2013) 381–384. arXiv:1310.7988 doi:10.1038/nature12767.
[25] F. Pepe, A. C. Cameron, D. W. Latham, E. Molinari, S. Udry, A. S. Bonomo, L. A. Buchhave, D. Charbonneau, R. Cosentino, C. D. Dressing, X. Dumusque, P. Figueira, A. F. M. Fiorenzano, S. Gettel, A. Harutyunyan, R. D. Haywood, K. Horne, M. Lopez-Morales, C. Lovis, L. Malavolta, M. Mayor, G. Micela, F. Motalebi, V. Nascimbeni, D. Phillips, G. Piotto, D. Pollacco, D. Queloz, K. Rice, D. Sasselov, D. Ségransan, A. Sozzetti, A. Szentygyorgyi, C. A. Watson, An Earth-sized planet with an Earth-like density, Nature503 (2013) 377–380. arXiv:1310.7987, doi:10.1038/nature12768.

[26] A. P. Hatzes, The detection of Earth-mass planets around active stars. The mass of Kepler-78b, A&A568 (2014) A84. arXiv:1407.0853, doi:10.1051/0004-6361/201424025.

[27] S. K. Grunblatt, A. W. Howard, R. D. Haywood, Determining the Mass of Kepler-78b with Nonparametric Gaussian Process Estimation, ApJ808 (2015) 127. arXiv:1501.00369, doi:10.1088/0004-637X/808/2/127.

[28] R. Sanchis-Ojeda, S. Rappaport, J. N. Winn, A. Levine, M. C. Kotson, D. W. Latham, L. A. Buchhave, Transits and Occultations of an Earth-sized Planet in an 8.5 hr Orbit, ApJ774 (2013) 54. arXiv:1305.4180, doi:10.1088/0004-637X/774/1/54.

[29] C. Moutou, J.-F. Donati, D. Lin, R. O. Laine, A. Hatzes, The magnetic properties of the star Kepler-78, MNRAS459 (2016) 1993–2007. arXiv:1605.03255, doi:10.1093/mnras/stw809.

[30] R. O. Laine, D. N. C. Lin, Interaction of Close-in Planets with the Magnetosphere of Their Host Stars. II. Super-Earths as Unipolar Inductors and Their Orbital Evolution, ApJ745 (2012) 2. arXiv:1201.1584, doi:10.1088/0004-637X/745/1/2.

[31] P. Goldreich, S. Soter, Q in the Solar System, Icarus5 (1966) 375–389. doi:10.1016/0019-1035(66)90051-0.

[32] K. C. Patra, J. N. Winn, M. J. Holman, L. Yu, D. Deming, F. Dai, The Apparently Decaying Orbit of WASP-12b, AJ154 (2017) 4. arXiv:1703.06582, doi:10.3847/1538-3881/aa6d75.

[33] D. Rouan, H. J. Deeg, O. Demangeon, B. Samuel, C. Cavarroc, B. Fegley, A. Léger, The Orbital Phases and Secondary Transits of Kepler-10b. A Physical Interpretation Based on the Lava-ocean Planet Model, ApJL741 (2011) L30. arXiv:1109.2768, doi:10.1088/2041-8205/741/2/L30.

[34] E. S. Kite, B. Fegley, Jr., L. Schaefer, E. Gaidos, Atmosphere-interior Exchange on Hot, Rocky Exoplanets, ApJ828 (2016) 80. arXiv:1606.06740, doi:10.3847/0004-637X/828/2/80.

[35] S. E. Gelman, L. T. Elkins-Tanton, S. Seager, Effects of Stellar Flux on Tidally Locked Terrestrial Planets: Degree-1 Mantle Convection and Local Magma Ponds, ApJ735 (2011) 72. doi:10.1088/0004-637X/735/2/72.
[36] F. W. Wagner, N. Tosi, F. Sohl, H. Rauer, T. Spohn, Rocky super-Earth interiors. Structure and internal dynamics of CoRoT-7b and Kepler-10b, A&A541 (2012) A103. doi:10.1051/0004-6361/201118441.

[37] E. D. Lopez, J. J. Fortney, Re-inflated Warm Jupiters around Red Giants, ApJ818 (2016) 4. arXiv:1510.00067, doi:10.3847/0004-637X/818/1/4.

[38] J. E. Owen, Y. Wu, Atmospheres of Low-mass Planets: The “Boil-off”, ApJ817 (2016) 107. arXiv:1506.02049, doi:10.3847/0004-637X/817/2/107.

[39] H. Chen, L. A. Rogers, Evolutionary Analysis of Gaseous Sub-Neptune-mass Planets with MESA, ApJ831 (2016) 180. arXiv:1603.06596, doi:10.3847/0004-637X/831/2/180.

[40] E. D. Lopez, J. J. Fortney, N. Miller, How Thermal Evolution and Mass-loss Sculpt Populations of Super-Earths and Sub-Neptunes: Application to the Kepler-11 System and Beyond, ApJ761 (2012) 59. arXiv:1205.0010, doi:10.1088/0004-637X/761/1/59.

[41] L. Schaefer, B. Fegley, Chemistry of Silicate Atmospheres of Evaporating Super-Earths, ApJL703 (2009) L113–L117. arXiv:0906.1204, doi:10.1088/0004-637X/703/2/L113.

[42] X. Huang, G. Á. Bakos, J. D. Hartman, 150 new transiting planet candidates from Kepler Q1-Q6 data, MNRAS429 (2013) 2001–2018. arXiv:1205.6492, doi:10.1093/mnras/sts463.

[43] J. N. Winn, R. Sanchis-Ojeda, L. Rogers, E. A. Petigura, A. W. Howard, H. Isaacson, G. W. Marcy, K. C. Schlaufman, P. Cargile, L. Hebb, Absence of a Metallicity Effect for Ultra-short-period Planets, AJ154 (2017) 60. arXiv:1704.00203, doi:10.3847/1538-3881/aa7b7c.

[44] M. S. Lundkvist, H. Kjeldsen, S. Albrecht, G. R. Davies, S. Basu, D. Huber, A. B. Justesen, C. Karoff, V. Silva Aguirre, V. van Eylen, C. Vang, T. Arntoft, T. Barclay, T. R. Bedding, T. L. Campante, W. J. Chaplin, J. Christensen-Dalsgaard, Y. P. Elsworth, R. L. Gilliland, R. Handberg, S. Hekker, S. D. Kawaler, M. N. Lund, T. S. Metcalfe, A. Miglio, J. F. Rowe, D. Stello, B. Tingley, T. R. White, Hot super-Earths stripped by their host stars, Nature Communications 7 (2016) 11201. arXiv:1604.05220, doi:10.1038/ncomms11201.

[45] J. H. Steffen, J. L. Coughlin, A Population of planetary systems characterized by short-period, Earth-sized planets, Proceedings of the National Academy of Science 113 (2016) 12023–12028. arXiv:1610.03550, doi:10.1073/pnas.1606658113.

[46] E. R. Adams, B. Jackson, M. Endl, Ultra-short-period Planets in K2 SuPerPiG Results for Campaigns 0-5, AJ152 (2016) 47. arXiv:1603.06488, doi:10.3847/0004-6256/152/2/47.
[47] C. D. Dressing, A. Vanderburg, J. E. Schlieder, I. J. M. Crossfield, H. A. Knutson, E. R. Newton, D. R. Ciardi, B. J. Fulton, E. J. Gonzales, A. W. Howard, H. Isaacson, J. Livingston, E. A. Petigura, E. Sinukoff, M. Everett, E. Horch, S. B. Howell, Characterizing K2 Candidate Planetary Systems Orbiting Low-mass Stars. II. Planetary Systems Observed During Campaigns 1-7, AJ154 (2017) 207. arXiv:1703.07416 doi:10.3847/1538-3881/aa89f2

[48] O. Barragán, D. Gandolfi, F. Dai, J. Livingston, C. M. Persson, T. Hirano, N. Narita, S. Csizmadia, J. N. Winn, D. Nespral, J. Prieto-Arranz, A. M. S. Smith, G. Nowak, S. Albrecht, G. Antoniciello, A. Bo Justesen, J. Cabrera, W. D. Cochran, H. Deeg, P. Eigmuller, M. Endl, A. Erikson, M. Fridlund, A. Fukui, S. Grziwa, E. Guenther, A. P. Hatzes, D. Hidalgo, M. C. Johnson, J. Korth, E. Palle, M. Patzold, H. Rauer, Y. Tanaka, V. Van Eylen, K2-141 b. A 5-M\textsubscript{\textoplus} super-Earth transiting a K7 V star every 6.7 h, A&A612 (2018) A95. arXiv:1711.02097 doi:10.1051/0004-6361/201732217

[49] E. W. Guenther, O. Barragán, F. Dai, D. Gandolfi, T. Hirano, M. Fridlund, L. Fossati, A. Chau, R. Helled, J. Korth, J. Prieto-Arranz, D. Nespral, G. Antoniciello, H. Deeg, M. Hjorth, S. Grziwa, S. Albrecht, A. P. Hatzes, H. Rauer, S. Csizmadia, A. M. S. Smith, J. Cabrera, N. Narita, P. Arriagada, J. Burt, R. P. Butler, W. D. Cochran, J. D. Crane, P. Eigmüller, A. Erikson, J. A. Johnson, A. Küblerich, D. Kubyshkina, E. Palle, C. M. Persson, M. Patzold, S. Sabotta, B. Sato, S. A. Shectman, J. K. Teske, I. B. Thompson, V. Van Eylen, G. Nowak, A. Vanderburg, J. N. Winn, R. A. Wittenmyer, K2-106, a system containing a metal-rich planet and a planet of lower density, A&A608 (2017) A93. arXiv:1705.04163 doi:10.1051/0004-6361/201730885

[50] F. Dai, J. N. Winn, D. Gandolfi, S. X. Wang, J. K. Teske, J. Burt, S. Albrecht, O. Barragán, W. D. Cochran, M. Endl, M. Fridlund, A. P. Hatzes, T. Hirano, L. A. Hirsch, M. C. Johnson, A. B. Justesen, J. Livingston, C. M. Persson, J. Prieto-Arranz, A. Vanderburg, R. Alonso, G. Antoniciello, P. Arriagada, R. P. Butler, J. Cabrera, J. D. Crane, F. Cusano, S. Csizmadia, H. Deeg, S. B. Dieterich, P. Eigmüller, A. Erikson, M. E. Everett, A. Fukui, S. Grziwa, E. W. Guenther, G. W. Henry, S. B. Howell, J. A. Johnson, J. Korth, M. Kuzuhara, N. Narita, D. Nespral, G. Nowak, E. Palle, M. Patzold, H. Rauer, P. Montaños Rodríguez, S. A. Shectman, A. M. S. Smith, I. B. Thompson, V. Van Eylen, M. W. Williamson, R. A. Wittenmyer, The Discovery and Mass Measurement of a New Ultra-short-period Planet: K2-131b, AJ154 (2017) 226. arXiv:1710.00076 doi:10.3847/1538-3881/aa9085

[51] L. Malavolta, A. W. Mayo, T. Louden, V. M. Rajpaul, A. S. Bonomo, L. A. Buchhave, L. Kreidberg, M. H. Kristiansen, M. Lopez-Morales, A. Mortier, A. Vanderburg, A. Coffinet, D. Ehrenreich, C. Lovis, E. Bouchy, D. Charbonneau, D. R. Ciardi, A. Collier Cameron, R. Cosentino, I. J. M. Crossfield, M. Damasso, C. D. Dressing, X. Dumusque, M. E. Everett, P. Figueira, A. F. M. Fiorenzano, E. J. Gonzales, R. D. Haywood, A. Harutyunyan, L. Hirschi, S. B. Howell, J. A. Johnson, D. W. Latham, E. Lopez, M. Mayor, G. Micela, E. Molinari, V. Nascimbeni, F. Pepe, D. F. Phillips, G. Piotto, K. Rice, D. Sasselov,
D. Segransan, A. Sozzetti, S. Udry, C. Watson, An Ultra-short Period Rocky Super-Earth with a Secondary Eclipse and a Neptune-like Companion around K2-141, AJ155 (2018) 107. arXiv:1801.03502, doi:10.3847/1538-3881/aaa5b5

[52] F. Fressin, G. Torres, D. Charbonneau, S. T. Bryson, J. Christiansen, C. D. Dressing, J. M. Jenkins, L. M. Walkowicz, N. M. Batalha, The False Positive Rate of Kepler and the Occurrence of Planets, ApJ766 (2013) 81. arXiv:1301.0842, doi:10.1088/0004-637X/766/2/81

[53] C. D. Dressing, D. Charbonneau, The Occurrence of Potentially Habitable Planets Orbiting M Dwarfs Estimated from the Full Kepler Dataset and an Empirical Measurement of the Detection Sensitivity, ApJ807 (2015) 45. arXiv:1501.01623, doi:10.1088/0004-637X/807/1/45

[54] A. W. Howard, G. W. Marcy, S. T. Bryson, J. M. Jenkins, J. F. Rowe, N. M. Batalha, W. J. Borucki, D. G. Koch, E. W. Dunham, T. N. Gautier, III, J. Van Cleve, W. D. Cochran, D. W. Latham, J. J. Lissauer, G. Torres, T. M. Brown, R. L. Gilliland, L. A. Buchhave, D. A. Caldwell, J. Christensen-Dalsgaard, D. Ciardi, F. Fressin, M. R. Haas, S. B. Howell, H. Kjeldsen, S. Seager, L. Rogers, D. D. Sasselov, J. H. Steffen, G. S. Basri, D. Charbonneau, J. Christiansen, B. Clarke, A. Dupree, D. C. Fabrycky, D. A. Fischer, E. B. Ford, J. J. Fortney, J. Tarter, F. R. Girouard, M. J. Holman, J. A. Johnson, T. C. Klaus, P. Machalek, A. V. Moorhead, R. C. Morehead, D. Ragozzine, P. Tenenbaum, J. D. Twicken, S. N. Quinn, H. Isaacson, A. Shporer, P. W. Lucas, L. M. Walkowicz, W. F. Welsh, A. Boss, E. Devore, A. Gould, J. C. Smith, R. L. Morris, A. Prsa, T. D. Morton, E. Sinukoff, I. J. M. Crossfield, L. A. Hirsch, The California-Kepler Survey. III. A Gap in the Radius Distribution of Small Planets, AJ154 (2017) 109. arXiv:1703.2541, doi:10.3847/1538-3881/aa80eb

[55] J. E. Owen, Y. Wu, The Evaporation Valley in the Kepler Planets, ApJ847 (2017) 29. arXiv:1705.10810, doi:10.3847/1538-3378/aa890a

[56] B. J. Fulton, E. A. Petigura, A. W. Howard, H. Isaacson, G. W. Marcy, P. A. Cargile, L. Hebb, L. M. Weiss, J. A. Johnson, T. D. Morton, E. Sinukoff, I. J. M. Crossfield, L. A. Hirsch, The California-Kepler Survey. III. A Gap in the Radius Distribution of Small Planets, AJ154 (2017) 109. arXiv:1703.10375, doi:10.3847/1538-3881/aa80eb

[57] J. E. Owen, Y. Wu, The Evaporation Valley in the Kepler Planets, ApJ847 (2017) 29. arXiv:1705.10810, doi:10.3847/1538-3378/aa890a

[58] B. J. Davidsson, Tidal Splitting and Rotational Breakup of Solid Spheres, Icarus142 (1999) 525–535. doi:10.1016/0019-1023(99)10014-4

[59] K. A. Holsapple, P. Michel, Tidal disruptions: A continuum theory for solid bodies, Icarus183 (2006) 331–348. doi:10.1016/j.icarus.2006.03.013
[60] L. Zeng, D. D. Sasselov, S. B. Jacobsen, Mass-Radius Relation for Rocky Planets Based on PREM, ApJ819 (2016) 127. arXiv:1512.08827, doi:10.3847/0004-637X/819/2/127

[61] L. M. Weiss, L. A. Rogers, H. T. Isaacson, E. Agol, G. W. Marcy, J. F. Rowe, D. Kipping, B. J. Fulton, J. J. Lissauer, A. W. Howard, D. Fabrycky, Revised Masses and Densities of the Planets around Kepler-10, ApJ819 (2016) 83. arXiv:1601.06168, doi:10.3847/0004-637X/819/1/83

[62] R. D. Haywood, A. Collier Cameron, D. Queloz, S. C. C. Barros, M. Deleuil, R. Fares, M. Gillon, A. F. Lanza, C. Lovis, C. Moutou, F. Pepe, D. Pollacco, A. Santerne, D. Ségransan, Y. C. Unruh, Planets and stellar activity: hide and seek in the CoRoT-7 system, MNRAS443 (2014) 2517–2531. arXiv:1407.1044, doi:10.1093/mnras/stu1320

[63] B.-O. Demory, M. Gillon, N. Madhusudhan, D. Queloz, Variability in the super-Earth 55 Cnc e, MNRAS455 (2016) 2018–2027. arXiv:1505.00269, doi:10.1093/mnras/stv2239

[64] E. Sinukoff, A. W. Howard, E. A. Petigura, B. J. Fulton, I. J. M. Crossfield, H. Isaacson, E. Gonzales, J. R. Crepp, J. M. Brewer, L. Hirsch, L. M. Weiss, D. R. Ciardi, J. E. Schlieder, B. Benneke, J. L. Christiansen, C. D. Dressing, B. M. S. Hansen, H. A. Knutson, M. Kosiarek, J. H. Livingston, T. P. Greene, L. A. Rogers, S. Lépine, K2-66b and K2-106b: Two Extremely Hot Sub-Neptune-size Planets with High Densities, AJ153 (2017) 271. arXiv:1705.03491, doi:10.3847/1538-3881/aa725f

[65] A. Vanderburg, J. C. Becker, L. A. Buchhave, A. Mortier, E. Lopez, L. Malavolta, R. D. Haywood, D. W. Latham, D. Charbonneau, M. López-Morales, F. C. Adams, A. S. Bonomo, F. Bouchy, A. Collier Cameron, R. Cosentino, L. Di Fabrizio, X. Dumusque, A. Fiorenzano, A. Harutyunyan, J. A. Johnson, V. Lorenzi, C. Lovis, M. Mayor, G. Micela, E. Molinari, M. Pedani, F. Pepe, G. Piotto, D. Phillips, K. Rice, D. Sasselov, D. Ségransan, A. Sozzetti, S. Udry, C. Watson, Precise Masses in the WASP-47 System, AJ154 (2017) 237. arXiv:1710.00026, doi:10.3847/1538-3881/aa918b

[66] D. Gandolfi, O. Barragán, A. P. Hatsze, M. Fridlund, L. Fossati, P. Donati, M. C. Johnson, G. Nowak, J. Prieto-Arranz, S. Albrecht, F. Dai, H. Deeg, M. Endl, S. Grziwa, M. Hjorth, J. Korth, D. Nespral, J. Saario, A. M. S. Smith, G. Antoniello, J. Alarcon, M. Bedell, P. Blay, S. S. Brems, J. Cabrera, C. Czesla, F. Cusano, W. D. Cochran, P. Eigmüller, A. Erikson, J. I. González Hernández, E. W. Guenther, T. Hirano, A. Suárez Mascareño, N. Narita, E. Palomba, H. Parviainen, M. Pätzold, C. M. Persson, H. Rauer, I. Saviane, L. Schmidtobreick, V. Van Eylen, J. N. Winn, O. V. Zakhazhov, The Transiting Multi-planet System HD 3167: A 5.7 M\textsubscript{\textoplus} Super-Earth and an 8.3 M\textsubscript{\textoplus} Mini-Neptune, AJ154 (2017) 123. arXiv:1706.02532, doi:10.3847/1538-3881/aa832a

[67] J. L. Christiansen, A. Vanderburg, J. Burt, B. J. Fulton, K. Batygin, B. Benneke, J. M. Brewer, D. Charbonneau, D. R. Ciardi, A. Collier Cameron, J. L.
Coughlin, I. J. M. Crossfield, C. Dressing, T. P. Greene, A. W. Howard, D. W. Latham, E. Molinari, A. Mortier, F. Mullally, F. Pepe, K. Rice, E. Sinukoff, A. Sozzetti, S. E. Thompson, S. Udry, S. S. Vogt, T. S. Barman, N. E. Batalha, F. Bouchy, L. A. Buchhave, R. P. Butler, R. Cosentino, T. J. Dupuy, D. Ehrenreich, A. Fiorenzano, B. M. S. Hansen, T. Henning, L. Hirsch, B. P. Holden, H. T. Isaacson, J. A. Johnson, H. A. Knutson, M. Kosiarek, M. López-Morales, C. Lovis, L. Malavolta, M. Mayor, G. Micela, F. Motalebi, E. Petigura, D. F. Phillips, G. Piotto, L. A. Rogers, D. Sasselov, J. E. Schlieder, D. Ségransan, C. A. Watson, L. M. Weiss, Three’s Company: An Additional Non-transiting Super-Earth in the Bright HD 3167 System, and Masses for All Three Planets, AJ154 (2017) 122. arXiv:1706.01892, doi:10.3847/1538-3881/aa832d.

[68] A. Santerne, B. Brugger, D. J. Armstrong, V. Adibekyan, J. Lillo-Box, H. Gosselin, A. Aguichine, J.-M. Almenara, D. Barrado, S. C. C. Barros, D. Bayliss, I. Boisse, A. S. Bonomo, F. Bouchy, D. J. A. Brown, M. Deleuil, E. Delgado Menà, O. Demangeon, R. F. Díaz, A. Doyle, X. Dumusque, F. Faedi, J. P. Faria, P. Figueira, E. Foxell, H. Giles, G. Hébrard, S. Hojjatpanah, M. Hobson, J. Jackman, G. King, J. Kirk, K. W. F. Lam, R. Ligi, C. Lovis, T. Louden, J. McCormac, O. Mousis, J. J. Neal, H. P. Osborn, F. Pepe, D. Pollacco, N. C. Santos, S. G. Sousa, S. Udry, A. Vigan, An Earth-sized exoplanet with a Mercury-like composition, Nature Astronomy 2 (2018) 393–400. arXiv:1805.08405, doi:10.1038/s41550-018-0420-5.

[69] B.-O. Demory, M. Gillon, S. Seager, B. Benneke, D. Deming, B. Jackson, Detection of Thermal Emission from a Super-Earth, ApJL751 (2012) L28. arXiv:1205.1766 doi:10.1088/2041-8205/751/2/L28.

[70] B.-O. Demory, M. Gillon, J. de Wit, N. Madhusudhan, E. Bolmont, K. Heng, T. Kataria, N. Lewis, R. Hu, J. Krick, V. Stamenković, B. Benneke, S. Kane, D. Queloz, A map of the large day-night temperature gradient of a super-Earth exoplanet, Nature532 (2016) 207–209. arXiv:1604.05725 doi:10.1038/nature17169.

[71] E. A. Petigura, G. W. Marcy, J. N. Winn, L. M. Weiss, B. J. Fulton, A. W. Howard, E. Sinukoff, H. Isaacson, T. D. Morton, J. A. Johnson, The California-Kepler Survey. IV. Metal-rich Stars Host a Greater Diversity of Planets, AJ155 (2018) 89. arXiv:1712.04042 doi:10.3847/1538-3881/aaa54c.

[72] G. D. Mulders, I. Pascucci, D. Apai, A. Frasca, J. Molenda-Zakowicz, A Supersolar Metallicity for Stars with Hot Rocky Exoplanets, AJ152 (2016) 187. arXiv:1609.05898 doi:10.3847/0004-6256/152/6/187.

[73] R. F. Wilson, J. Teske, S. R. Majewski, K. Cunha, V. Smith, D. Souto, C. Bender, S. Mahadevan, N. Truop, C. Allende Prieto, K. G. Stassun, M. F. Skrutskie, A. Almeida, D. A. García-Hernández, O. Zamora, J. Brinkmann, Elemental Abundances of Kepler Objects of Interest in APOGEE. I. Two Distinct Orbital Period Regimes Inferred from Host Star Iron Abundances, AJ155 (2018) 68. arXiv:1712.01198 doi:10.3847/1538-3881/aa9f27.
[74] F. Valsecchi, S. Rappaport, F. A. Rasio, P. Marchant, L. A. Rogers, Tidally-driven Roche-lobe Overflow of Hot Jupiters with MESA, ApJ813 (2015) 101. arXiv:1506.05175, doi:10.1088/0004-637X/813/2/101

[75] A. Königl, S. Giacalone, T. Matsakos, On the Origin of Dynamically Isolated Hot Earths, ApJL846 (2017) L13. arXiv:1708.08159, doi:10.3847/2041-8213/aa861f

[76] T. D. Morton, S. T. Bryson, J. L. Coughlin, J. F. Rowe, G. Ravichandran, E. A. Petigura, M. R. Haas, N. M. Batalha, False Positive Probabilities for all Kepler Objects of Interest: 1284 Newly Validated Planets and 428 Likely False Positives, ApJ822 (2016) 86. arXiv:1605.02825, doi:10.3847/0004-637X/822/2/86

[77] J. F. Rowe, S. T. Bryson, G. W. Marcy, J. J. Lissauer, D. Jontof-Hutter, F. Mullally, R. L. Gilliland, H. Isaacson, E. Ford, S. B. Howell, W. J. Borucki, M. Haas, D. Huber, J. H. Steffen, S. E. Thompson, E. Quintana, T. Barclay, M. Still, J. Fortney, T. N. Gautier, III, R. Hunter, D. A. Caldwell, D. R. Ciardi, E. Devore, W. Cochran, J. Jenkins, E. Agol, J. A. Carter, J. Geary, Validation of Kepler’s Multiple Planet Candidates. III. Light Curve Analysis and Announcement of Hundreds of New Multi-planet Systems, ApJ784 (2014) 45. arXiv:1402.6534, doi:10.1088/0004-637X/784/1/45

[78] J. D. Twicken, J. M. Jenkins, S. E. Seader, P. Tenenbaum, J. C. Smith, L. S. Brownston, C. J. Burke, J. H. Catanzarite, B. D. Clarke, M. T. Cote, F. R. Girouard, T. C. Klaus, J. Li, S. D. McCauliff, R. L. Morris, B. Wohler, J. R. Campbell, A. Kamal Uddin, K. A. Zamudio, A. Sabale, S. T. Bryson, D. A. Caldwell, J. L. Christiansen, J. L. Coughlin, M. R. Haas, C. E. Henze, D. T. Sanderfer, S. E. Thompson, Detection of Potential Transit Signals in 17 Quarters of Kepler Data: Results of the Final Kepler Mission Transiting Planet Search (DR25), AJ152 (2016) 158. arXiv:1604.06140, doi:10.3847/0004-6256/152/6/158

[79] P. S. Muirhead, J. A. Johnson, K. Apps, J. A. Carter, T. D. Morton, D. C. Fabrycky, J. S. Pineda, M. Bottom, B. Rojas-Ayala, E. Schlawin, K. Hamren, K. R. Covey, J. R. Crepp, K. G. Stassun, J. Pepper, L. Hebb, E. N. Kirby, A. W. Howard, H. T. Isaacson, G. W. Marcy, D. Levitan, T. Diaz-Santos, L. Armus, J. P. Lloyd, Characterizing the Cool KOIs. III. KOI 961: A Small Star with Large Proper Motion and Three Small Planets, ApJ747 (2012) 144. arXiv:1201.2189, doi:10.1088/0004-637X/747/2/144

[80] E. R. Adams, B. Jackson, M. Endl, W. D. Cochran, P. J. MacQueen, D. A. Duev, R. Jensen-Clem, M. Salama, C. Ziegler, C. Baranec, S. Kulkarni, N. M. Law, R. Riddle, Ultra-short-period Planets in K2 with Companions: A Double Transiting System for EPIC 220674823, AJ153 (2017) 82. arXiv:1611.00397, doi:10.3847/1538-3881/153/2/82

[81] D. C. Fabrycky, E. B. Ford, J. H. Steffen, J. F. Rowe, J. A. Carter, A. V. Moorhead, N. M. Batalha, W. J. Borucki, S. Bryson, L. A. Buchhave, J. L.
Christiansen, D. R. Ciardi, W. D. Cochran, M. Endl, M. N. Fanelli, D. Fischer, F. Fressin, J. Geary, M. R. Haas, J. R. Hall, M. J. Holman, J. M. Jenkins, D. G. Koch, D. W. Latham, J. Li, J. J. Lissauer, P. Lucas, G. W. Marcy, T. Mazeh, S. McCauliffe, S. Quinn, D. Ragozzine, D. Sasselov, A. Shporer, Transit Timing Observations from Kepler. IV. Confirmation of Four Multiple-planet Systems by Simple Physical Models, ApJ750 (2012) 114. arXiv:1201.5415, doi:10.1088/0004-637X/750/2/114.

[82] A. W. Mayo, A. Vanderburg, D. W. Latham, A. Bieryla, T. D. Morton, L. A. Buchhave, C. D. Dressing, C. Beichman, P. Berlind, M. L. Calkins, D. R. Ciardi, I. J. M. Crossfield, G. A. Esquerdo, M. E. Everett, E. J. Gonzales, L. A. Hirsch, E. P. Horch, A. W. Howard, S. B. Howell, J. Livingston, R. Patel, E. A. Petigura, J. E. Schlieder, N. J. Scott, C. F. Schumer, E. Sinukoff, J. Teske, J. G. Winters, 275 Candidates and 149 Validated Planets Orbiting Bright Stars in K2 Campaigns 0–10, AJ155 (2018) 136. arXiv:1802.05277, doi:10.3847/1538-3881/aaadff.

[83] A. Vanderburg, A. Bieryla, D. A. Duev, R. Jensen-Clem, D. W. Latham, A. W. Mayo, C. Baranec, P. Berlind, S. Kulkarni, N. M. Law, M. N. Nieberding, R. Riddle, M. Salama, Two Small Planets Transiting HD 3167, ApJL829 (2016) L9. arXiv:1607.05248 doi:10.3847/2041-8205/829/1/L9.

[84] J. C. Becker, A. Vanderburg, F. C. Adams, S. A. Rappaport, H. M. Schwengeler, WASP-47: A Hot Jupiter System with Two Additional Planets Discovered by K2, ApJL812 (2015) L18. arXiv:1508.02411 doi:10.1088/2041-8205/812/2/L18.

[85] M. G. MacDonald, D. Ragozzine, D. C. Fabrycky, E. B. Ford, M. J. Holman, H. T. Isaacson, J. J. Lissauer, E. D. Lopez, T. Mazeh, L. Rogers, J. F. Rowe, J. H. Steffen, G. Torres, A Dynamical Analysis of the Kepler-80 System of Five Transiting Planets, AJ152 (2016) 105. arXiv:1607.07540 doi:10.3847/0004-6256/152/4/105.

[86] J. H. Steffen, D. Ragozzine, D. C. Fabrycky, J. A. Carter, E. B. Ford, M. J. Holman, J. F. Rowe, W. F. Welsh, W. J. Borucki, A. P. Boss, D. R. Ciardi, S. N. Quinn, Kepler constraints on planets near hot Jupiters, Proceedings of the National Academy of Science 109 (2012) 7982–7987. arXiv:1205.2309 doi:10.1073/pnas.1120970109.

[87] D. C. Fabrycky, J. J. Lissauer, D. Ragozzine, J. F. Rowe, J. H. Steffen, E. Agol, T. Barclay, N. Batalha, W. Borucki, D. R. Ciardi, E. B. Ford, T. N. Gautier, J. C. Geary, M. J. Holman, J. M. Jenkins, J. Li, R. C. Morehead, R. L. Morris, A. Shporer, J. C. Smith, M. Still, J. Van Cleve, Architecture of Kepler’s Multi-transiting Systems. II. New Investigations with Twice as Many Candidates, ApJ790 (2014) 146. arXiv:1202.6328 doi:10.1088/0004-637X/790/2/146.
[88] J. H. Steffen, W. M. Farr, A Lack of Short-period Multiplanet Systems with Close-proximity Pairs and the Curious Case of Kepler-42, ApJL774 (2013) L12. arXiv:1306.3526 doi:10.1088/2041-8205/774/1/L12.

[89] J. E. Rodriguez, J. C. Becker, J. D. Eastman, S. Hadden, A. Vanderburg, T. Khain, S. N. Quinn, A. Mayo, C. D. Dressing, J. E. Schlieder, D. R. Ciardi, D. W. Latham, S. Rappaport, F. C. Adams, P. Berlind, A. Bieryla, M. L. Calkins, G. A. Esquerdo, M. H. Kristiansen, M. Omohundro, H. M. Schwengeler, K. G. Stassun, I. Terentev, A Compact Multi-planet System with a Significantly Mis-aligned Ultra Short Period Planet, AJ156 (2018) 245. arXiv:1806.08368 doi:10.3847/1538-3881/aae530.

[90] F. Dai, K. Masuda, J. N. Winn, Larger Mutual Inclinations for the Shortest-period Planets, ApJL864 (2018) L38. arXiv:1808.08475 doi:10.3847/2041-8213/aadd4f.

[91] S. N. Raymond, R. Barnes, A. M. Mandell, Observable consequences of planet formation models in systems with close-in terrestrial planets, MNRAS384 (2008) 663–674. arXiv:0711.2015 doi:10.1111/j.1365-2966.2007.12712.x.

[92] K. C. Schlaufman, D. N. C. Lin, S. Ida, A Population of Very Hot Super-Earths in Multiple-planet Systems Should be Uncovered by Kepler, ApJL724 (2010) L53–L58. arXiv:1010.3705 doi:10.1088/2041-8205/724/1/L53.

[93] C. Petrovich, E. Deibert, Y. Wu, Ultra-short-period planets from secular chaos, arXiv e-prints arXiv:1804.05065.

[94] L. Hebb, A. Collier-Cameron, A. H. M. J. Triaud, T. A. Lister, B. Smalley, P. F. L. Maxted, C. Hellier, D. R. Anderson, D. Pollacco, M. Gillon, D. Queloz, R. G. West, S. Bentley, B. Enoch, C. A. Haswell, K. Horne, M. Mayor, F. Pepe, D. Segransan, I. Skillen, S. Udry, P. J. Wheatley, WASP-19b: The Shortest Period Transiting Exoplanet Yet Discovered, ApJ708 (2010) 224–231. arXiv:1001.0403 doi:10.1088/0004-637X/708/1/224.

[95] G. Maciejewski, D. Dimitrov, M. Fernández, A. Sota, G. Nowak, J. Ohlert, G. Nikolov, Ł. Bukowiecki, T. C. Hinse, E. Pallé, B. Tingley, D. Kjurkchieva, J. W. Lee, C.-U. Lee, Departure from the constant-period ephemeris for the transiting exoplanet WASP-12, A&A588 (2016) L6. arXiv:1602.09056 doi:10.1051/0004-6361/201628312.

[96] J. C. van Eyken, D. R. Ciardi, K. von Braun, S. R. Kane, P. Plavchan, C. F. Bender, T. M. Brown, J. R. Crepp, B. J. Fulton, A. W. Howard, S. B. Howell, S. Mahadevan, G. W. Marcy, A. Shporer, P. Szkody, R. L. Akeson, C. A. Beichman, A. F. Boden, D. M. Gelino, D. W. Hoard, S. V. Ramírez, L. M. Rebull, J. R. Stauffer, J. S. Bloom, S. B. Cenko, M. M. Kasliwal, S. R. Kulkarni, N. M. Law, P. E. Nugent, E. O. Ofek, D. Poznanski, R. M. Quimby, R. Walters, C. J. Grillmair, R. Laher, D. B. Levitan, B. Sesar, J. A. Surace, The PTF
Orion Project: A Possible Planet Transiting a T-Tauri Star, ApJ755 (2012) 42. [106] arXiv:1206.1510 doi:10.1088/0004-637X/755/1/42

[97] J. W. Barnes, J. C. van Eyken, B. K. Jackson, D. R. Ciardi, J. J. Fortney, Measurement of Spin-orbit Misalignment and Nodal Precession for the Planet around Pre-main-sequence Star PTFO 8-8695 from Gravity Darkening, ApJ774 (2013) 53. arXiv:1308.0629 doi:10.1088/0004-637X/774/1/53

[98] D. R. Ciardi, J. C. van Eyken, J. W. Barnes, C. A. Beichman, S. J. Carey, C. C. Crockett, J. Eastman, C. M. Johns-Krull, S. B. Howell, S. R. Kane, J. N. McLane, P. Plavchan, L. Prato, J. Stauffer, G. T. van Belle, K. von Braun, Follow-up Observations of PTFO 8-8695: A 3 Myr Old T-Tauri Star Hosting a Jupiter-mass Planetary Candidate, ApJ809 (2015) 42. arXiv:1506.08719 doi:10.1088/0004-637X/809/1/42

[99] L. Yu, J. N. Winn, M. Gillon, S. Albrecht, S. Rappaport, A. Bieryla, F. Dai, L. Delrez, L. Hillenbrand, M. J. Holman, A. W. Howard, C. X. Huang, H. Isaacson, E. Jehin, M. Lendl, B. T. Montet, P. Muirhead, R. Sanchis-Ojeda, A. H. M. J. Trijau, Tests of the Planetary Hypothesis for PTFO 8-8695b, ApJ812 (2015) 48. arXiv:1509.02176 doi:10.1088/0004-637X/812/1/48

[100] C. M. Johns-Krull, L. Prato, J. N. McLane, D. R. Ciardi, J. C. van Eyken, W. Chen, J. R. Stauffer, C. A. Beichman, S. A. Frazier, A. F. Boden, M. Morales-Calderón, L. M. Rebull, Hα Variability in PTFO8-8695 and the Possible Direct Detection of Emission from a 2 Million Year Old Evaporating Hot Jupiter, ApJ830 (2016) 15. arXiv:1606.02701 doi:10.3847/0004-637X/830/1/15

[101] S. Charpinet, G. Fontaine, P. Brassard, E. M. Green, V. Van Grootel, S. K. Randall, R. Silvotti, A. S. Baran, R. H. Østensen, S. D. Kawaler, J. H. Teltling, A compact system of small planets around a former red-giant star, Nature480 (2011) 496–499. doi:10.1038/nature10631

[102] J. Krzesinski, Planetary candidates around the pulsating sdB star KIC 5807616 considered doubtful, A&A581 (2015) A7. doi:10.1051/0004-6361/201526346

[103] S. Rappaport, A. Levine, E. Chiang, I. El Mellah, J. Jenkins, B. Kalomeni, E. S. Kite, M. Kotson, L. Nelson, L. Rousseau-Nepton, K. Tran, Possible Disintegrating Short-period Super-Mercury Orbiting KIC 12557548, ApJ752 (2012) 1. arXiv:1201.2662 doi:10.1088/0004-637X/752/1/1

[104] S. Rappaport, T. Barclay, J. DeVore, J. Rowe, R. Sanchis-Ojeda, M. Still, KOI-2700b A Planet Candidate with Dusty E Allison on a 22 hr Orbit, ApJ784 (2014) 40. arXiv:1312.2054 doi:10.1088/0004-637X/784/1/40

[105] R. Sanchis-Ojeda, S. Rappaport, E. Pallè, L. Delrez, J. DeVore, D. Gandolfi, A. Fukui, I. Ribas, K. G. Stassun, S. Albrecht, F. Dai, E. Gaidos, M. Gillon, T. Hirano, M. Holman, A. W. Howard, H. Isaacson, E. Jehin, M. Kuzuhara,
A. W. Mann, G. W. Marcy, P. A. Miles-Páez, P. Montañés-Rodríguez, F. Murgas, N. Narita, G. Nowak, M. Onitsuka, M. Paegert, V. Van Eylen, J. N. Winn, L. Yu, The K2-ESPRINT Project I: Discovery of the Disintegrating Rocky Planet K2-22b with a Cometary Head and Leading Tail, ApJ812 (2015) 112. arXiv:1504.04379, doi:10.1088/0004-637X/812/2/112

[106] R. van Lieshout, S. Rappaport, Disintegrating Rocky Exoplanets, 2017, p. 15. doi:10.1007/978-3-319-30648-3_15-2

[107] D. Perez-Becker, E. Chiang, Catastrophic evaporation of rocky planets, MN-RAS433 (2013) 2294–2309. arXiv:1302.2147, doi:10.1093/mnras/stt895

[108] A. Vanderburg, J. A. Johnson, S. Rappaport, A. Bieryla, J. Irwin, J. A. Lewis, D. Kipping, W. R. Brown, P. Dufour, D. R. Ciardi, R. Angus, L. Schaefer, D. W. Latham, D. Charbonneau, C. Beichman, J. Eastman, N. McCrady, R. A. Wittenmyer, J. T. Wright, A disintegrating minor planet transiting a white dwarf, Nature526 (2015) 546–549. arXiv:1510.06387, doi:10.1038/nature15527

[109] S. Xu, S. Rappaport, R. van Lieshout, A. Vanderburg, B. Gary, N. Hallakoun, V. D. Ivanov, M. C. Wyatt, J. DeVore, D. Bayliss, J. Bento, A. Bieryla, A. Cameron, J. M. Cann, B. Croll, K. A. Collins, P. A. Dalba, J. Debes, D. Doyle, P. Dufour, J. Ely, N. Espinoza, M. D. Joner, M. Jura, T. Kaye, J. L. McClain, P. Muirhead, E. Palle, P. A. Panka, J. Provencal, S. Randall, J. E. Rodriguez, J. Scarborough, R. Sefako, A. Shporer, W. Strickland, G. Zhou, B. Zuckerman, A dearth of small particles in the transiting material around the white dwarf WD 1145+017, MNRAS474 (2018) 4795–4809. arXiv:1711.06960, doi:10.1093/mnras/stx3023

[110] G. R. Ricker, J. N. Winn, R. Vanderspek, D. W. Latham, G. Á. Bakos, J. L. Bean, Z. K. Berta-Thompson, T. M. Brown, L. Buchhave, N. R. Butler, R. P. Butler, W. J. Chaplin, D. Charbonneau, J. Christensen-Dalsgaard, M. Clampin, D. Deming, J. Doty, N. De Lee, C. Dressing, E. W. Dunham, M. Endl, F. Fressin, J. Ge, T. Henning, M. J. Holman, A. W. Howard, S. Ida, J. M. Jenkins, G. Jernigan, J. A. Johnson, L. Kaltenegger, N. Kawai, H. Kjeldsen, G. Laughlin, A. M. Levine, D. Lin, J. J. Liessauer, P. MacQueen, G. Marcy, P. R. McCullough, T. D. Morton, N. Narita, M. Paegert, E. Palle, F. Pepe, J. Pepper, A. Quirrenbach, S. A. Rinehart, D. Sasselov, B. Sato, S. Seager, A. Sozzetti, K. G. Stassun, P. Sullivan, A. Szentesgyorgyi, G. Torres, S. Udry, J. Villasenor, Transiting Exoplanet Survey Satellite (TESS), Journal of Astronomical Telescopes, Instruments, and Systems 1 (1) (2015) 014003. doi:10.1117/1.JATIS.1.1.014003