Origins: From the Protosun to the First Steps of Life
Proceedings IAU Symposium No. 345, 2018
B. G. Elmegreen, L. Viktor Tóth & M. Güdel, eds.

doi:10.1017/S1743921319001637

Characterization and Properties of Earth-like Planets

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Abstract. The search for life in the Universe is intertwined with studies of extrasolar planets aimed at identifying and understanding habitable rocky planets, including those similar in size, bulk composition, planetary environment, and evolution to Earth. The past five years have seen dramatic progress in our understanding of the small (1–4 R_{Earth}) planet population. Here we briefly review key results on the occurrence rates of small planets, the first evidence for compositional diversity of these worlds, early results on the characterization of their atmospheres, and the progress toward finding and interpreting potentially habitable planets orbiting the closest stars. We also briefly highlight next steps in furthering our understanding of the origins and properties of habitable worlds.

Keywords. astrobiology, planetary systems, planetary systems: formation

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Perhaps no other field of astrophysics has seen a progress as dramatic as the studies of sub-jovian exoplanets over the past decade. Advances are particularly exciting in the exploration of potentially rocky and habitable planets, which lays the foundation for one of the grandest experiments conceivable: the search for signatures of life in planetary systems beyond our own. This contribution aims to review the latest advances and exciting next steps in our quest to understand the diversity of small (1–4 R_{Earth}) exoplanets, with special emphasis on the identification and characterization of potentially habitable rocky worlds – worlds that may be Earth-like.

1. Occurrence Rate of Small Planets

One of the most fundamental and strategically important questions in the search of Earth-like planets is the occurrence rate of Earth-sized, habitable zone planets around sun-like stars. This value – referred to as η_{Earth} – is central not only to our understanding of exoplanetary systems, but also to identify the optimal strategy for discovering and characterizing candidate Earth-like planets. A high η_{Earth} value may make a single combined search–and–characterization approach viable, while a low η_{Earth} would likely necessitate a two-stage approach.

NASA's Kepler mission has transformed the field of exoplanets through its capability of robustly detecting small exoplanets (e.g., Batalha 2014). Kepler's primary science goal was to determine η_{Earth}. To measure this value it searched for transiting planets around ∼170,000 stars. Kepler has detected hundreds of small planets, including many Earth-sized and even sub-Earth-sized planets. Yet, the total sample of known Earth-sized planets in habitable zones of sun-like stars remains small due to the limited duration of

Kepler's primary mission. Therefore, most estimates of η_{Earth} are based on extrapolations of samples dominated by larger-than-Earth and closer-in planets, often in the habitable zones of lower-mass stars. As different groups' estimates rely on different assumptions and on different versions of the Kepler data set, different η_{Earth} estimates have emerged reflecting broad range of possible answers.

Although the exact occurrence rates of Earth-sized planets around sun-like stars remains to be determined, we can conclude with reasonably high confidence that η_{Earth} cannot be small (i.e., $\eta_{Earth} > 10^{-2}$), and may even be close to unity.

Importantly, Kepler detection statistics has revealed important differences between the architectures of planetary systems around higher- and lower-mass stars. Dressing & Charbonneau (2015) noted that the occurrence rates of small planets around M-type stars is higher than that in the combined sample of F, G, and K-type host stars. Mulders *et al.* (2015a) showed that, in fact, short-period, small planet occurrence rates are a monotonic function of host star mass – surprisingly, F, G, K, and M-type stars host small planets at progressively increasing rates (i.e., inversely proportionally with stellar mass). Mulders *et al.* (2015b) also found that not only does the average number of short-period small planets increase with decreasing stellar mass, but that planetary systems around later spectral type stars also have more solid mass in their planets than those around earlier spectral type stars.

While the community discussion on η_{Earth} has not yet been settled conclusively, a meta-study has been carried out by the Study Analysis Group 13 of the NASA EXOPAG† to seek a consensus range. This study (Belikov *et al.* 2017) contrasted the methodology, assumptions, and datasets that underpinned the different estimates. The meta-study included results and methodology from many individual groups (including, for example, Petigura *et al.* 2013, Kopparapu 2013, Dressing & Charbonneau 2015, Mulders *et al.* 2015a, Burke *et al.* 2015). The three key findings of the SAG13 study are as follows: (1) The precise definition of η_{Earth} – such as host spectral type range, planet radius range, and habitable zone boundaries – has major impact on the derived η_{Earth} values. (2) With this in mind the SAG13 defined their own η_{Earth} (for 0.5–1.5 R_{Earth}, G spectral type, extended habitable zone boundaries per Kopparapu 2014). (3) With consistent methodology and based on same or similar datasets, multiple individual teams find similar η_{Earth} values, albeit with significant uncertainty. The SAG13 team suggests adopting an $\eta_{Earth} \sim 0.6$, but cautions that the value is sensitive to the factors described above.

These are profound results as they suggest that Earth-sized habitable planets in the Galaxy may number between tens of millions to tens of billions (including stars of all spectral types). They also mean that it is likely that habitable zone earth-sized planets are relatively common in the solar neighborhood.

As this manuscript is being prepared for submission, the revolution in small exoplanet discovery is entering its next stage with NASA's TESS mission. Over time, it is likely that the planet detections and insights gained from the TESS mission will help to further refine our best estimates for η_{Earth}.

2. Compositional Diversity of Small Planets

While the nature of most small planets remains poorly known, limited but nevertheless valuable insights could be gained through the determination of their bulk densities. Bulk density can be determined for planets that are transiting *and* also detected via stellar radial velocity (RV) measurements: while the former enables relative measurements of the planet's radii, the latter provides relative measurements of the planets'

† https://exoplanets.nasa.gov/exep/exopag/overview/

https://doi.org/10.1017/S1743921319001637 Published online by Cambridge University Press

masses. As both measurements are more challenging for smaller planets than for larger ones, the sample of small planets with both measurements is a small, but slowly growing one.

Bulk density measurements allow placing constraints on the compositions of the planets. For example, Earth's bulk density is $\rho = 5.5$ g cm^{-3}, consistent with its interior dominated by an iron-rich core ($\rho = 9.9 - 13.1$ g cm^{-3}, 32.5w%) and silicate mantle and crust ($\rho = 4.5$g cm^{-3}, 67.47 w%). Neptune, on the other hand, has a much lower density ($\rho = 1.64$ g cm^{-3}), consistent with its volatile-rich composition (H_2: 80 wt%, He: 19 wt%, CH_4: 1 wt%). Extending this comparison to exoplanets, thus, can provide powerful insights into their bulk compositions. It is important, however, to note that bulk density is a degenerate measure of bulk composition: for most densities – even when considering only three key components – an infinite number of compositions can lead to the same density (Rogers & Seager 2010a). In fact, bulk density measurements are most constraining for outliers, i.e., very low or very high density worlds, where either high-density (silicates, iron) or low-density (hydrogen/helium, water) components must dominate. The range of compositions consistent with a measured bulk density and its uncertainties can be narrowed down if specific formation pathways can be identified (e.g., Rogers & Seager 2010b)

The California–Kepler Survey has studied 2,205 Kepler exoplanet host stars with high-resolution optical spectroscopy to refine the stellar radii, often the largest uncertainty in these Kepler-detected exoplanets' radii (as transits measure R_p/R_s, planet radius relative to the stellar radius). The spectroscopic characterization enabled an improvement in the precision with which planets' radii are measured, leading to a median uncertainty of 12%. This improved precision revealed a pattern in planet size distribution that was indiscernible in previous datasets (Fulton *et al.* 2017). A striking feature seen in this distribution is a bimodal size distribution for small planets. The depleted planet occurrence rate around radii of $R_p = 1.6\ R_\oplus$ (often referred to as the *Fulton gap*), is a highly significant feature. The presence of the Fulton gap has been confirmed by subsequent studies (e.g., Hsu *et al.* 2018), including a study that further characterized the host stars by combining spectroscopic classification with GAIA-measured distances (Fulton *et al.* 2018). The presence of such a gap has been predicted by atmospheric photoevaporation models (e.g., Lopez & Fortney 2014, Chen & Howard 2016, Owen & Wu 2017) and are also explained by models in which tenuous atmospheres can be lost due to heating by the planetary core (Ginzburg *et al.* 2018).

Particularly exciting examples of small planets in the solar neighborhood are found in the TRAPPIST-1 system (Gillon *et al.* 2016, Gillon *et al.* 2017). This system includes seven, roughly Earth-sized planets. The relative sizes of the planets can be derived from their transit depths as measured in the 3.6 μm Spitzer/IRAC band (less sensitive to stellar heterogeneities than shorter wavelengths measurements, Rackham *et al.* 2018). This multi-planet system is so tightly packed that very significant transit timing variations are observable, which allow for refined planet mass measurements (e.g., Agol & Deck 2016). Due to the complexity of the system and the strengths of the gravitational interactions between the planets, finding masses from transit timing variations is a highly non-linear and challenging task; on the other hand, the gradually increasing temporal baseline and increasing number of transits observed enables increasingly precise models. A detailed study by Grimm *et al.* (2018) modeled the accumulated transit timing variation data and derived relatively high-precision mass estimates for the planets. Combined with the planet radii measurements, these allowed the comparisons of the bulk densities of the TRAPPIST-1 worlds. The relatively high densities of planets *c* and *e* suggest that these worlds are rocky, while the other planets are more likely to have significant gaseous envelopes or large mass fractions of water.

3. Atmospheric Characterization

Exoplanets that transit their host stars also offer an opportunity to study the host star's light as it filters through the planets' atmospheres (e.g., Seager & Deming 2010, Heng & Kitzmann 2018). At wavelengths where planets' atmospheres can absorb the planets will be effectively larger in size (optical depth $\tau = 1$ is reached higher in the atmosphere). Therefore, by measuring the wavelength-dependence of the planets' size (transit depth), key absorbers can be identified or inferred.

However, such wavelength-dependent modulations of the time-dependent intensity modulations introduced by planetary transits (small signals in themselves) are very challenging to measure. While ground-based telescopes have proved to be powerful tools in studying the atmospheres of hot jupiters, sub-jovian planets remained accessible to only a few instruments that combined sensitivity and photometric stability (or ability to measure and correct for instrumental and atmospheric systematics).

The Hubble Space Telescope's WFC3 instrument's near-infrared camera has proved to be a particularly powerful instrument for transit spectroscopy. Reaching essentially photon-noise-limited performance, the atmospheres of. even small planets' can be explored for water vapor absorption. Kreidberg *et al.* (2014) has demonstrated the feasibility of co-adding spectral data from twelve transits of the sub-neptune GJ 1214b, while efficiently correcting for detector and telescope systematics. de Wit *et al.* (2016) and de Wit *et al.* (2018) used the same instrument to explore, for the first time, the transmission spectra of habitable zone, approximately Earth-sized planets, targeting six worlds in the TRAPPIST-1 system. These studies found no evidence for water absorption (in the planets' atmospheres) but, at least in the case of GJ1214, offered strong evidence for high-altitude hazes that weaken near-infrared molecular absorption features.

Given the successes of HST/WFC3 infrared spectroscopy of transiting planets, it may be tempting to think that by carefully correcting for instrument systematics, future instruments will allow us to reach photon-noise-limited precision for small transiting planets. However, this may not be the case: there are important astrophysical systematics that may limit the precision of transit spectroscopy before photon noise limit can be reached. An important source of such systematics are the host stars themselves. It has been long recognized that starspots – even if not occulted by the planet – will impact the transmission spectra (e.g., Pont *et al.* 2008, Sing *et al.* 2016). This effect was often considered likely negligible or correctable for transiting hot jupiters. However, with the increasing precision demanded by small exoplanets, this systematics has been revisited by Rackham *et al.* (2018). This study described the *transit lightsource effect*, the contamination of the transiting exoplanet transmission spectra due to a spectral difference between the integrated spectrum of the transit chord (actual lightsource) and the disk-integrated spectrum of the host star (the observable property). *Any* heterogeneity on the star will introduce a spectral difference between the two, thereby contaminating the transmission spectrum (see Figure 1). Understanding and correcting for the transit light source effect is essential for future characterization of small exoplanets (Apai *et al.* 2018).

Important examples of the transit light source effect were described in visual spectra of the sub-neptune GJ 1214b (Rackham *et al.* 2017) and in the approximately Earth-sized planets orbiting TRAPPIST-1 (Zhang *et al.* 2018). The latter study showed that the combined dataset of ground-based photometry, HST/WFC3 spectra, and Spitzer/IRAC transit depth measurement can be best modeled with stellar contamination due to hotter faculae and large starspots on TRAPPIST-1. In a follow-up study, Wakeford *et al.* (2018) explored a number of possible configurations for the stellar heterogeneity and how these would affect the planet's apparent transmission spectra.

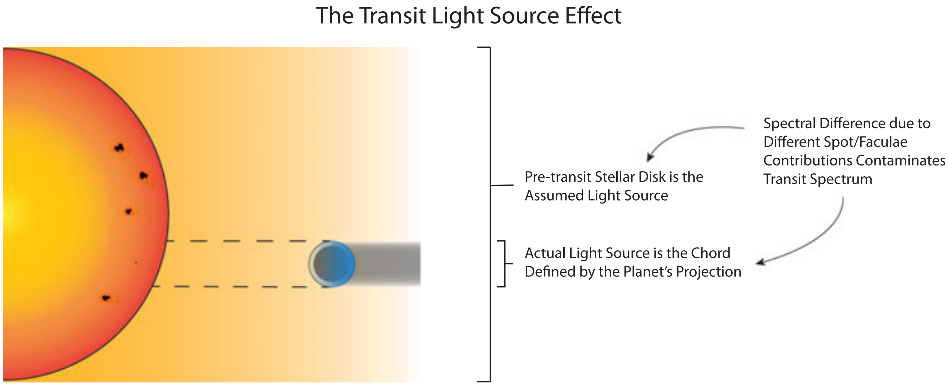

Figure 1. The transit light source (TLS) effect is the contamination of exoplanet transmission spectra. The effective contamination occurs because the light source of the transmission spectroscopy (transit light chord) has a spectra different from the disk-integrated spectrum of the star (directly observable quantity). TLS can introduce apparent slopes and molecular features in the transmission spectra of planets; the effect is particularly problematic for late-type host stars and small planets. Modified from Rackham *et al.* (2018).

4. Understanding Potentially Habitable Worlds in our Neighborhood

The focus in the search for habitable planets is increasingly shifting to stars close to the Solar System: While Kepler has explored systems typically between 0.5 to 1.5 kpc in order to provide statistical insights into the small planet population, studies aimed at discovering exoplanets that can be characterized in detail must look for targets within tens of parsecs from the Sun. NASA's TESS mission is expected to yield over ten thousand new exoplanet candidates (e.g., Sullivan *et al.* 2015, Barclay *et al.* 2018), many within a few hundred parsecs. Many of the TESS candidates will orbit bright enough host stars to allow characterization via transit spectroscopy. Simultaneously, increasingly sensitive ground-based transit surveys with 1m and larger telescopes (e.g., SPECULOOS†, EDEN‡) target nearby late red dwarf stars, where their telescopes can detect earth-sized transiting planets.

As transit searches are only sensitive to the subset of planetary systems with orbital planes close to edge on (as viewed from Earth), we must turn to other planet detection methods to complete our census of habitable planets in the solar neighborhood. Progress in precision radial velocity measurements recently enabled the detection of small-amplitude (m/s-level) velocity modulations in red dwarfs. This capability led to the detections of small planet candidates around the nearby stars Proxima Centauri b (Anglada-Escudé, G. *et al.* 2016), Barnard's Star (Ribas *et al.* 2018), and Ross 128 (Bonfils *et al.* 2018). Perhaps most exciting among these is Proxima. Not only is it the closest star to the Solar System, but its planet also orbits in the habitable zone and, even considering the activity of its host star and a likely tidally-locked state, it may be habitable (e.g., Meadows *et al.* 2018, Carone *et al.* 2018).

Proxima Cen b is a good example for the challenges we face when attempting to characterize habitable exoplanets in the next decades. Detection of these worlds remains challenging and – for the foreseeable future – we will always have only partial information on *very complex* systems, that may even include alien ecosystems. While our characterization of individual planets will remain greatly incomplete, we may be able to *interpret*

† https://www.speculoos.uliege.be/
‡ http://project-eden.space

https://doi.org/10.1017/S1743921319001637 Published online by Cambridge University Press

these worlds by combining specific measurements of the planet with *statistical contextual understanding* of small planets in general. In fact, through the thousands of planet detections emerging from Kepler and (soon) from TESS, and from microlensing (from WFIRST), over the next decades we shall develop a very good statistical understanding of the small planet population.

Bayesian probabilistic assessment provides a path forward to combine specific information on a planet with probabilistic priors that can represent the properties of the parent population. A study by Bixel & Apai (2016) demonstrated this principle on Proxima b and showed how planet occurrence rates measured for M-dwarf host stars by Kepler can help refine posterior probability distributions on Proxima b's mass and composition. Probabilistic Bayesian assessment of planets' nature can also include statistical predictions from planet formation and planet evolution (including interior and atmospheric evolution). The same or similar approach will likely be essential for interpreting future observations of small exoplanets, whether detected through direct imaging, transits, microlensing, or radial velocity surveys.

Important contextual information can be gained from planet formation and evolution models, as many properties of the small planets will not be directly observable even with powerful new telescope facilities. However, models that can explain the observed properties of the planet populations will provide a good basis to predict properties such as bulk composition or orbital evolution pathways, at least in a probabilistic sense. Indeed, multiple groups are developing large-scale planet formation simulations to aid such studies (e.g., PlanetS in Switzerland and the EOS/NExSS team in the US). With large databases of simulated planetary systems, statistical comparisons to the planet surveys is becoming possible. An important new tool enabling such comparisons is *EPOS* (Mulders *et al.* 2018), which simulates the entire Kepler mission (complete with its sensitivity, observing strategy, identification and confirmation biases) in a fraction of a second. Equipped with this tool, simulated hypothetical planet populations can be compared against the observations and models can be tested, optimized, and verified. The interpretation of observations of individual nearby exoplanets will greatly benefit from statistically verified planet formation/evolution models.

5. Next Steps

As rapid progress in astrobiology and exoplanet exploration continues, the quest for habitable planets and the search for life beyond the Solar System emerge as likely science goals for major ground- and space-based astronomical projects. Planets – especially ones with a prominent biosphere – are likely to be very complex systems. Identifying and interpreting them via purely remote sensing will require multi-disciplinary, comprehensive, and coordinated research. The characterization itself will require powerful new telescopes and instruments. Multiple reports with community input have been written over the past three years to identify science questions, opportunities, and critical milestones in this process. For example, the EXOPAG SAG reports reviewed science opportunities afforded by transiting exoplanets (Cowan *et al.* 2015), science questions for direct imaging missions (Apai *et al.* 2017), possible biosignatures and their interpretation (e.g., Meadows *et al.* 2018, Schwieterman *et al.* 2018, Catling *et al.* 2018, Fujii *et al.* 2018, Walker *et al.* 2018). Two new NASA-commissioned reports laid out a science strategy for studies of exoplanets and astrobiology (see NAS website). These and similar reports provide comprehensive overviews of the future of the field. Here we only highlight three key questions central to the search for life on other planets.

First, in considering future exoplanet missions aimed at understanding habitable exoplanets, when setting the required sample size of planets to be studied, it is paramount to consider the complexity of rocky planets. If too small samples of planets are studied, the risk of incomplete understanding – or even misinterpretation – of the observations will be high.

Second, understanding the stellar contamination emerging from the transit lightsource effect will be important to fully exploit the transit-based data – our only probes of the atmospheres of small planets prior to direct imaging missions.

Third, development of planet formation and planetary system evolution models that can reproduce every properties of the planet populations – as observed through transits, radial velocity, direct imaging, and microlensing – will likely be essential to correctly predict and, later, to interpret the diversity of small exoplanets.

Acknowledgements

The results reported herein benefited from collaborations and/or information exchange within NASA's Nexus for Exoplanet System Science (NExSS) research coordination network sponsored by NASA's Science Mission Directorate.

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Discussion

GÜNTHER: Have all rocky planets the composition like the Earth, or are there planets with a Mercury-like composition as derived from density measurements of exoplanets?

APAI: For most small planets with available bulk density measurements these are consistent with rocky (broadly Earth-like) or more volatile-rich composition. To my knowledge, there has been one Kepler-detected relatively massive planet with initial radial velocity measurements suggesting iron-like density.

KEDZIORA-CHUDCZER: Can you explain the featureless spectra for TRAPPIST- 1 by the existence of hazes or clouds in the atmosphere rather than stellar variability due to spots?

APAI: A featureless spectrum alone could be explained by a lack of atmosphere or by high-altitude hazes. However, the data show that the TRAPPIST-1 spectra are not featureless, but show features *opposite* in sign from what the planetary absorption could produce – i.e., it shows an inverse water absorption feature. Only stellar contamination is consistent with such a feature.