EPSC Abstracts
Vol. 11, EPSC2017-559-1, 2017
European Planetary Science Congress 2017

Towards accurate masses for the TRAPPIST-1 planets

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Abstract

We recently reported the discovery of a system of seven temperate Earth-sized planets transiting TRAPPIST-1, an ultra-cool dwarf star only 12 pc away. The Jupiter-size and infrared brightness of TRAPPIST-1 offers the extraordinary opportunity to thoroughly study the atmospheric properties of these worlds with present-day and future astronomical facilities. Interpretation of future atmospheric observations will depend crucially on the knowledge of the planets' masses, which can be constrained from their Transit Timing Variation (TTV) signals. In this context, we are currently pursuing intense efforts to collect further high-precision transit timings of all TRAPPIST-1 planets and refine their masses and dynamical properties. We will present here the results of this campaign and discuss the implications for the compositions and possible modes of formation of the TRAPPIST-1 planets, as well as for their tidal heating and orbital stability.

1. Enter TRAPPIST-1

We recently reported the discovery of a system of seven Earth-sized (0.72–1.13 $R_\oplus$) planets transiting TRAPPIST-1, a nearby (12 pc), middle-aged (3–8 Gyr) M8 dwarf star with a mass just 8% that of the Sun (Gillon et al. 2016, 2017; Luger et al. 2017). The stellar irradiations on the planets cover a range from 4.3 to 0.13 $S_\oplus$ (where $S_\oplus$ is the Solar irradiation at 1 AU), which is very similar to the one of the inner Solar System. All seven planets are temperate (equilibrium temperatures <400K) and the three planets TRAPPIST-1e, f, and g orbit in the habitable zone around the star (Kopparapu et al. 2013). The transiting configuration of the TRAPPIST-1 planets, combined with the small size (0.12 $R_\odot$), low luminosity (0.0005 $L_\odot$), and infrared brightness (K=10.3) of their host star, provides the extraordinary opportunity to thoroughly study their atmospheric properties with present-day (HST, *Spitzer*) and future (JWST, E-ELT) astronomical facilities (Barstow & Irwin 2016, de Wit et al. 2016). The TRAPPIST-1 system thus represents a unique opportunity to extend the nascent field of comparative exoplanetology into the realm of temperate Earth-sized worlds.

2. TTVs: The path towards precise planetary masses

Precise mass determinations of the planets and the resulting constraints on their raw compositions (e.g. Zeng et al. 2016) are critical for a thorough understanding of these worlds, and for the correct interpretation of future atmospheric observations (e.g. de Wit

& Seager 2013). Assessment of the planets' potential habitability makes it also necessary to measure their orbital eccentricities, to constrain the impact of tidal heating on their total energy budget, but also on their geological activity that could be able to counterbalance atmospheric erosion through volcanism.

The masses and eccentricities of TRAPPIST-1 planets can be measured from their Transit Timing Variations (TTVs, e.g. Agol et al. 2005, Holman et al. 2005). Remarkably, the seven planets form a near-resonant chain: all sets of three adjacent planets are in three-body resonances, implying notable mutual gravitational interactions between the planets. These interactions induce substantial TTVs (up to more than 30 minutes for the outer planets), whose dynamical modeling allows the individual planetary masses and eccentricities to be constrained.

In Gillon et al. (2017), we investigated photometric timing measurements obtained from the ground and with *Spitzer* and derived initial mass estimates for the six inner planets, along with upper limits on their orbital eccentricities. We obtained planetary masses comprised between 0.4 and 1.4 $M_{\oplus}$, although with large uncertainties, ranging from 30% to nearly 100%. This is due to the limited time baseline of the dataset studied then, which resulted in a degeneracy of the dynamical solution. We also found small ($e < 0.085$) but non-zero eccentricities, suggesting significant tidal heating of the planets.

Recently, Wang et al. (2017) presented an analysis supplementing our timing measurements with the 73.6 days of nearly-continuous TRAPPIST-1 photometry obtained by the K2 Mission from December 2016 to March 2017 (Luger et al. 2017). Figure 1 shows the planets in a mass-radius diagram based on both their mass measurements (blue dots) and ours (yellow dots). The planetary masses that they derived are in good overall agreement with our initial mass estimates and globally more precise. Theoretical mass-radius curves for planets with different compositions (Zeng et al. 2016) are also shown for comparison. The four outer planets are consistent with pure water compositions, suggesting volatile-rich compositions. Wang et al. (2017) also found eccentricities $e < 0.02$ for the six inner planets.

However, uncertainties are still substantial and these results must be verified. Further photometric transit follow-up is needed to better constrain the planetary masses and eccentricities and isolate a unique, well defined, dynamical solution. Only by gathering additional precise transit timings for all seven planets will we be able to attain a thorough understanding of the TRAPPIST-1 system.

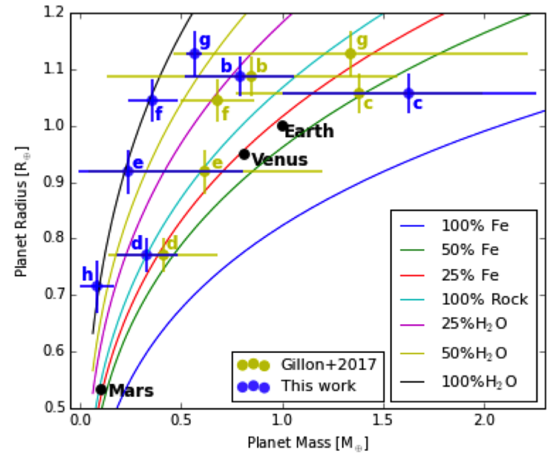

Figure 1: Mass-radius diagram of the TRAPPIST-1 planets. Transit timing-inferred masses from Gillon et al. (2017) are plotted as yellow dots, while the masses inferred by Wang et al. (2017) are plotted in blue. Theoretical mass-radius curves for planets with different compositions (Zeng et al. 2016) are shown for comparison. Figure from Wang et al. (2017).

3. Our ongoing TTV follow-up campaign

In this context, we are currently pursuing intense efforts to collect further high-precision transit timings of all TRAPPIST-1 planets. We already observed 65 new transits with *Spitzer* last February-March. In the upcoming months, we will complement these data with additional high-precision ground-based transit photometry that we will obtain with different facilities, such as the High Acuity Widefield K-band Imager (HAWK-I) on the 8m Very Large Telescope (VLT), the 3.8m UK InfraRed Telescope (UKIRT) and its infrared Wide-Field Camera (WFCAM), and the robotic 2m Liverpool Telescope. We will present here the results of this campaign and discuss the implications for the compositions and possible modes of formation of the TRAPPIST-1 planets, as well as for their tidal heating and orbital stability.

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