Detailed Stellar and Planetary Characterization of the Multiplanet Systems Kepler-278 and Kepler-391

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ABSTRACT

Kepler-278 and Kepler-391 are two of the three evolved stars known to date on the red giant branch (RGB) to host multiple short-period transiting planets. Moreover, the planets orbiting Kepler-278 and Kepler-391 are among the smallest discovered around RGB stars. Here we present a detailed stellar and planetary characterization of these remarkable systems. Based on high-quality spectra, we obtained refined stellar parameters and precise chemical abundances for 25 elements. Nine of these elements and the carbon isotopic ratios, had not previously been measured. Also, combining our new stellar parameters with a photodynamical analysis of the *Kepler* light curves, we determined accurate planetary properties of both systems. In particular, for Kepler-278, thanks to the presence of dynamical interactions in the system, we constrained, for the first time, the masses of the two planets. Full details about this work can be found in Jofré et al. (2020).

OBSERVATIONS

Spectroscopy: We obtained wide wavelength coverage (~400−1050 nm), high-resolution (R~67,500), and high signal-to-noise (S/N > 300) spectra of Kepler-278 and Kepler-391 with GRACES at the 8.1 m Gemini North telescope. A small portion of the reduced spectra of both stars is shown here.

Photometry: We retrieved the data release 25 of the *Kepler* light curves (Twicken et al. 2016) from the Mikulski Archive for Space Telescopes (MAST). Kepler-278 was observed from quarter Q1 to Q8 in long-cadence data, and from Q9 to Q17 in short-cadence data. Kepler-391 was observed from quarter Q0 to Q17 only in long-cadence data. We used the simple aperture photometry (SAP) light curve, which we corrected for the flux contamination using the value estimated by the *Kepler* team. An example of the observed transits and their fits can be seen here.

STELLAR CHARACTERIZATION

- From the high-quality spectroscopic data we derived precise stellar parameters and chemical abundances of 25 elements (Li, C, N, O, Na, Mg, Al, Si, S, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Sr, Y, Zr, Ba, and Ce), and the carbon isotopic ratio $^{12}C/^{13}C$. Overall, our stellar parameters agree reasonably well with most of the previous results. However, we find that Kepler-278 is ~15% less massive than recently reported (Mathur et al. 2017; Johnson et al. 2017; Fulton & Petigura 2018).
- The stellar parameters of both stars along with their measured carbon $^{12}C/^{13}C$ isotopic ratio reveal that both stars are just starting their ascent on the RGB as can be noticed in Figure 1. Also it can be notice that although there are several stars all along the RGB with planets detected from RV surveys, only a few late subgiants and early red giants (~15) are known to host transiting planets, which highlight the difficulty to detect planetary transits at this evolutionary stage.
- The chemical abundances of light, alpha, Fe-peak, and heavy elements of both stars follow the abundance trends of other evolved thin disk stars in the solar neighborhood. The lithium abundance of Kepler-391, ($A(Li)_{NLTE}$ = 1.29 ± 0.09 dex), is slightly below the standard limit of the rare Li-rich giant stars. The evolutionary state of this star, its low vsin i, and lack of other chemical peculiarities would support that the Li content of Kepler-391 is most likely a remnant from the main-sequence phase and not the consequence of a recent planetary engulfment episode or a fresh lithium production phase.
- The measured stellar metallicities for Kepler-278 ([Fe/H] = 0.22 dex) and Kepler-391 ([Fe/H] = 0.04 dex) are consistent with the tendency that small planets can occur around stars with a wide range of metallicities (e.g., Petigura et al. 2018). Also, according to the relatively low mineralogical ratio obtained for both stars ([Mg/Si] ~ 0), none of them would seem to follow the trend of higher [Mg/Si] ratios for hosts with small planets (Adibekyan et al. 2015).

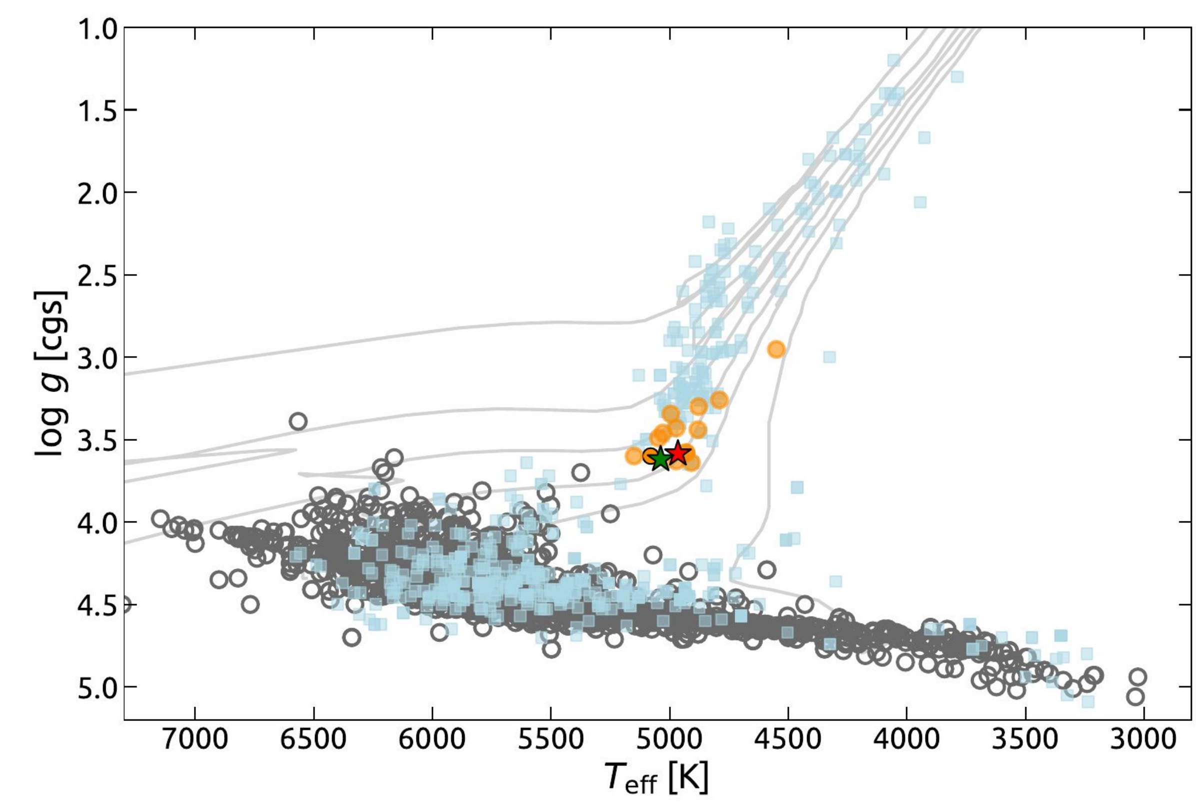


Figure 1: Location of Kepler-278 (red star) and Kepler-391 (green star) in the HR diagram, based on the spectroscopic $T_{\rm eff}$ and log g measured in this work, in comparison with other confirmed exoplanet hosts: light blue squares represent stars with confirmed planets detected via RVs, dark gray circles are stars with planets found by transits, and orange circles represent the small population of RGB stars with transiting planets. Error bars are omitted for clarity. Evolutionary tracks, corresponding to masses of 3, 2, 1.6, 1.3, 1.0, and 0.6 $M_\odot$ (left to right) for [Fe/H] = +0.0 dex, from Girardi et al. (2000) are overplotted with continuous lines.

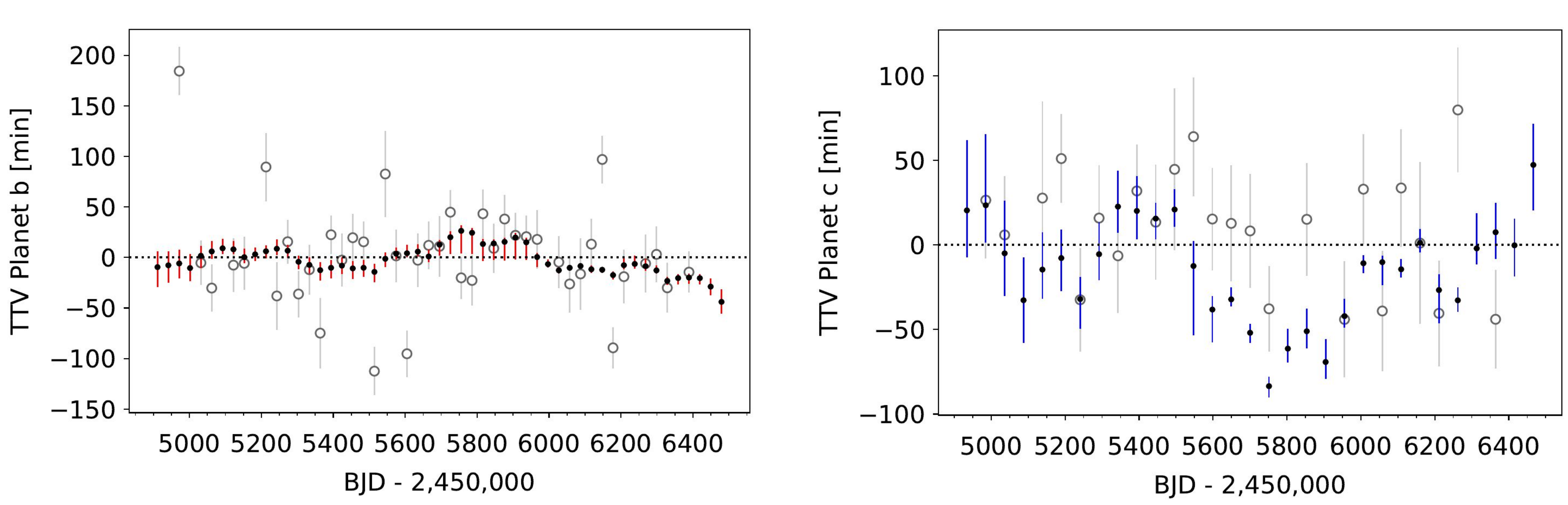


Figure 2: Posterior TTV of Kepler-278b (left panel, red) and Kepler-278c (right panel, blue) from the photodynamical modeling. For comparison the TTV of Rowe et al. (2015) measured on individual transits are shown as empty circles with grey error bars.

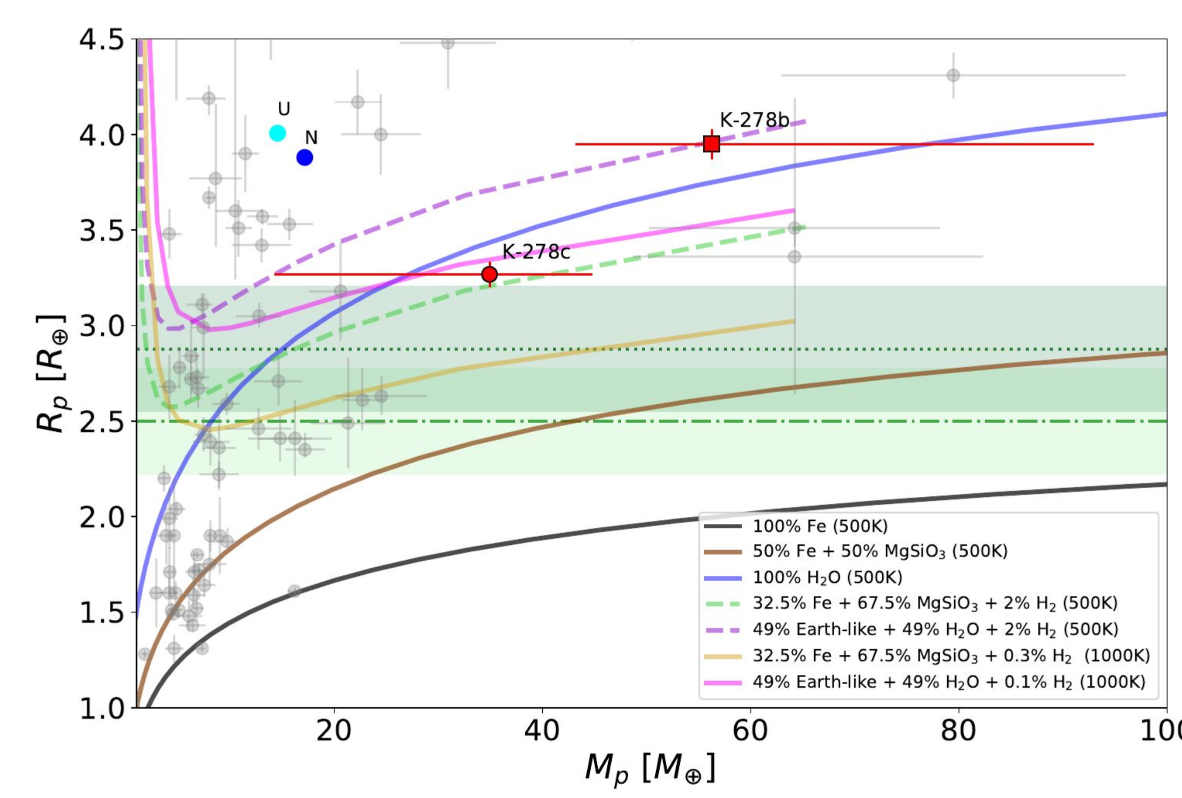


Figure 3: Mass–radius diagram for all confirmed planets with masses between 1–100 $M_\oplus$ and radii 1–4.5 $R_\oplus$ determined with a precision better than 30%. Theoretical composition models from Zeng et al. (2016) are displayed with different lines and colors. Kepler-278b is marked with a red square and Kepler-278c is indicated with red circle. Kepler-391b and Kepler-391c are indicated with dark and light green bands, respectively, that represent the 1σ uncertainty in our derived planetary radii. For reference, the solar system planets Uranus and Neptune are marked with a cyan and blue circle, respectively.

PLANETARY CHARACTERIZATION

- Using a photodynamical analysis of the *Kepler* light curves as described in Almenara et al. (2018), in combination with our new stellar parameters, we derived improved planetary properties. In particular, for the Kepler-278 system, the increased precision in the transit times obtained from this analysis allowed us to measure for the first time the masses of Kepler-278b ($M_p = 56^{+37}_{-13}\ M_\oplus$) and Kepler-278c ($M_p = 35^{+10}_{-21}\ M_\oplus$). Not only do we confirm the presence of a TTV signal in Kepler-278c (Figure 2, right), but also detect a previously unreported TTV signal in the inner planet Kepler-278b (Figure 2, left). For the system Kepler-391, given the lack of detected TTV signals, only upper limits on the masses could be provided. Additionally, the photodynamical analysis reveals that the orbits of both planets around Kepler-278 are surprisingly eccentric (e ~ 0.7) and coplanar, which pose a puzzle about its origin. A precise RV follow-up of Kepler-278 is needed to confirm the eccentricity values presented here. The complete set of derived planetary parameters of the Kepler-278 and Kepler-391 systems is shown here.
- Figure 3 shows the location of Kepler-278b and Kepler-278c in a mass-radius diagram compared to other relatively small transiting planets (Rp < 4.5 $R_\oplus$) with measured masses and radii better than 30%. Although the large uncertainties in the planetary masses of Kepler-278b/c (~50%) prevent us from performing a detailed analysis of their composition, their radii are precise enough to locate both planets completely above the regime of solid planets with pure-iron or Earth-like rocky composition. Instead, their bulk structures might be consistent with a significant amount of water content and the presence of H_2 gaseous envelopes. For the Kepler-391 system, given the lack of TTV signals, we cannot estimate the planetary masses and therefore both planets are indicated in Figure 3 with bands corresponding to their radii. However, considering the predicted masses from the mass–radius relation of Chen & Kipping (2017) these planets also might fall into the composition regimes consistent with a significant amount of water content or Earth-like rocky core and the presence of H_2 gaseous envelopes.
- Using our derived planetary parameters, in Figure 4 we located Kepler-278b/c and Kepler-391b/c in the radius-flux diagram. According to their radii and orbital period, Kepler-278b, Kepler-278c, and Kepler-391c would be classified as warm sub-Neptunes. Kepler-391b is a warm sub-Neptune that resides just inside the rightmost boundary of the hot super-Earth desert (Lundkvist et al. 2016). In case this planet has a bulk structure consistent with a significant amount of water content or H_2 gaseous envelope, this may be suffering photoevaporation. It is expected that this process increases in a few Myr as its host star continues ascending on the RGB.
- Planets Kepler-278b/c and Kepler-391b/c are part of the small group of planets (~20), most of them detected via transits, in close-in orbits around evolved stars with a semi-major axis below ~0.5 AU (P ≲ 100 d). One of the main scenarios to explain the paucity of close-in planets considers that these objects might end up engulfed by their host stars as they ascend on the RGB (e.g., Villaver & Livio 2009). Based on our stellar parameters and evolutionary tracks from Girardi et al. (2000), we found that the stellar surface of Kepler-391 will reach the inner planet in ~410 Myr (≈17 $R_\odot$) and the outer planet in 428 Myr (≈63 $R_\odot$). Kepler-278, that is slightly more evolved than Kepler-391, will engulf its inner planet in ~408 Myr (≈43 $R_\odot$) and in ~428 Myr (≈63 $R_\odot$) the outer planet.

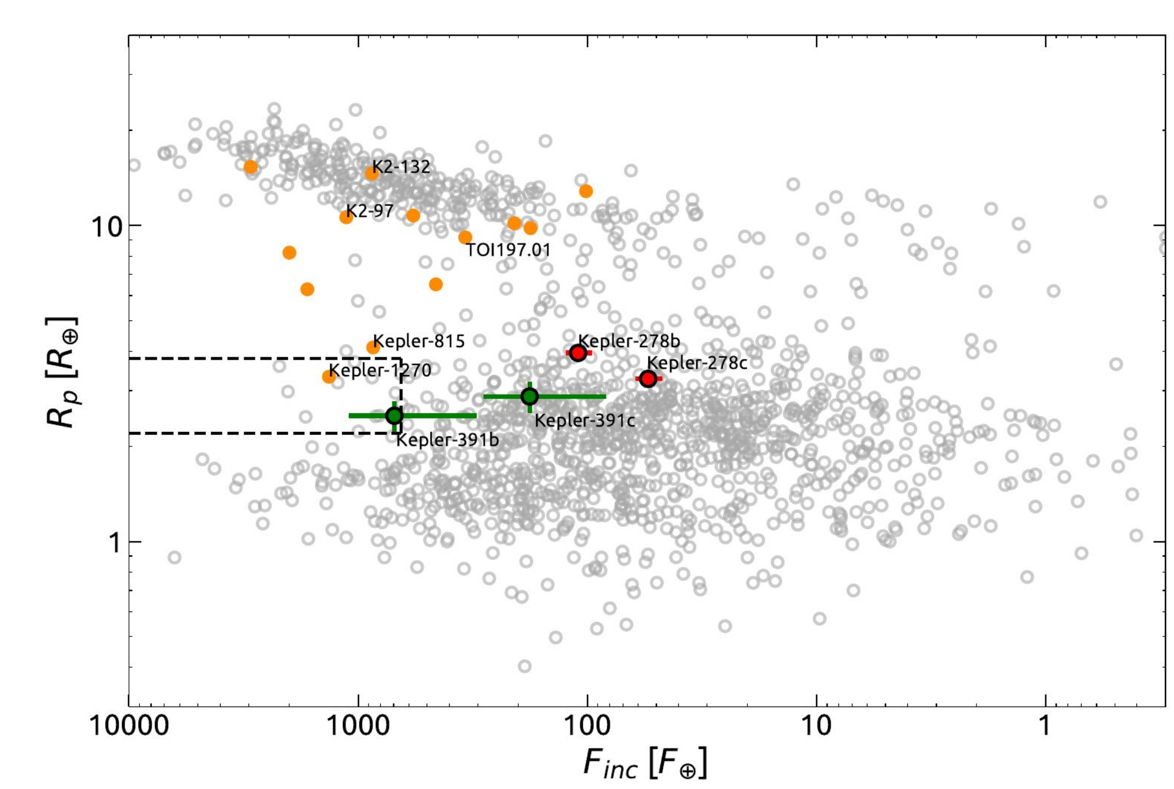
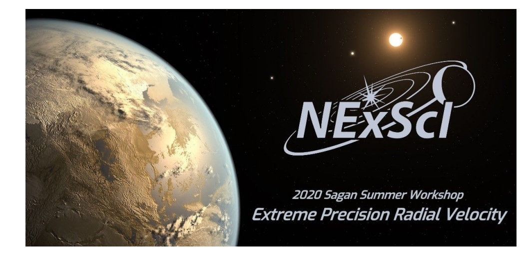


Figure 4: Planet radius versus incident flux for transiting confirmed exoplanets (grey circles). Planets around Kepler-278 and Kepler-391 are highlighted in red and green circles, respectively. Planets around RGB stars are indicated with filled orange circles. The black dashed lines delimit the super-Earth desert as derived in Lundkvist et al. (2016). Other planets around RGB stars are also labelled.



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