Terrestrial Exoplanet Internal Structure Constraints Are Not Limited by Host Star Spectroscopic Analysis

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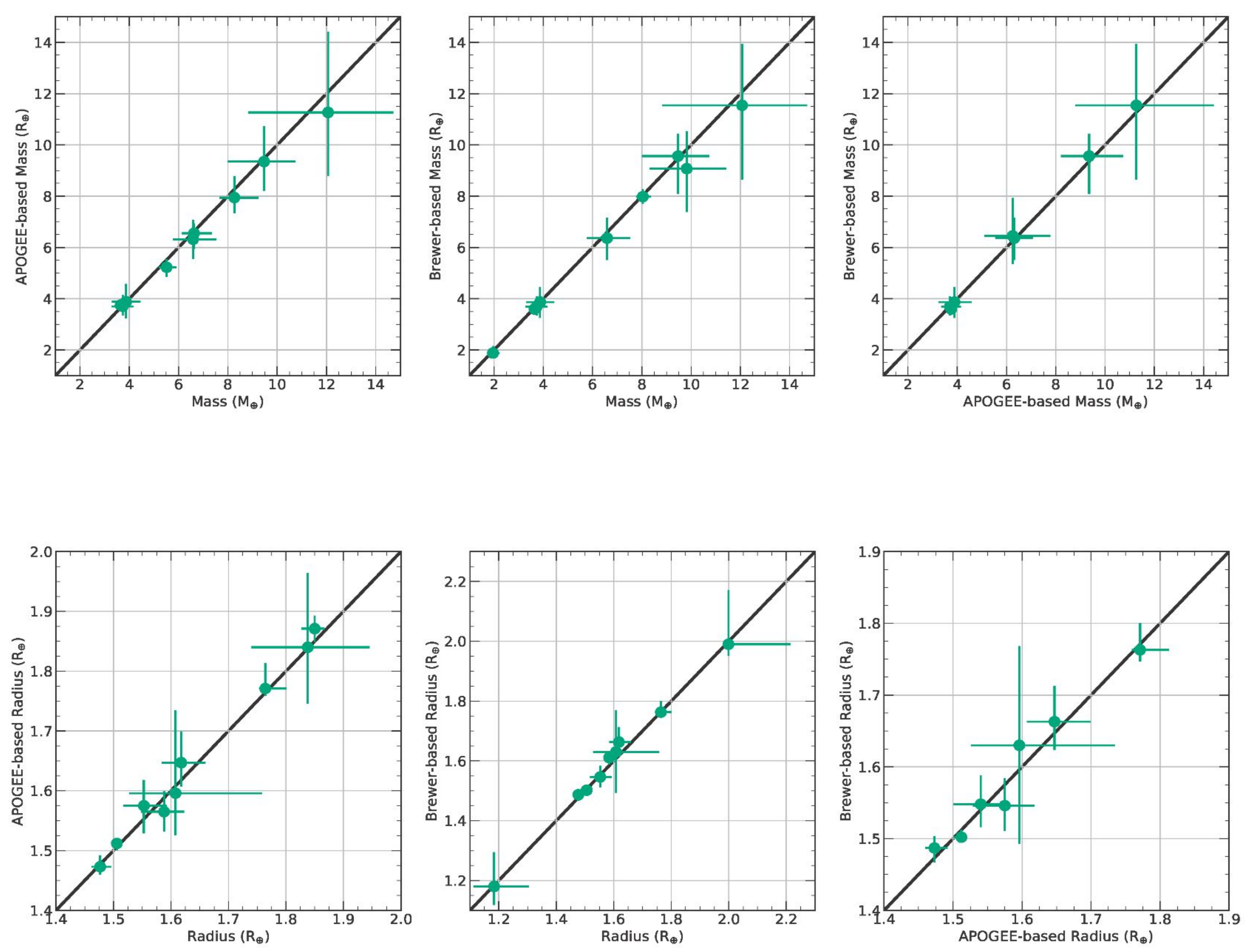
Abstract

Exoplanet mass and radius inferences, and therefore internal structure constraints, are based on host star mass and radius inferences. **Accurate, precise, homogeneous, and self-consistent exoplanet internal structure constraints therefore demand accurate, precise, homogeneous, and self-consistent host star mass, radius, and elemental abundance inferences.** Published terrestrial exoplanet internal structure constraints have often been based on host star mass, radius, and elemental abundance inferences that are not self-consistent. For 20 solar-type stars known to host terrestrial exoplanets, we use all available astrometric and photometric data plus high-resolution optical spectroscopy to infer accurate, precise, homogeneous, and self-consistent photospheric and fundamental stellar parameters as well as elemental abundances. **We infer updated planetary masses and radii using these data plus Doppler and transit observables and then use our complete data set to derive the strongest possible constraints on the internal structures of these terrestrial planets.** We repeat these same analyses using the high-quality catalogs of photospheric stellar parameters and elemental abundances from SDSS DR17 APOGEE and Brewer et al. (2016, 2018) to assess the impact of differing photospheric stellar parameters and elemental abundance inference approaches on terrestrial exoplanet internal structure modeling.

Photospheric Stellar Parameters

Designation	$T_{\rm eff}$ (K)	$\log g$ (cm s^{-2})	[Fe/H] (dex)	ξ (km s^{-1})	Stellar Mass ($M_\odot$)	Stellar Radius ($R_\odot$)	Planet Mass ($M_\oplus$)	Planet Radius ($R_\oplus$)
This Study								
K2-106	5455^{+19}_{-20}	$4.41^{+0.01}_{-0.01}$	$0.09^{+0.01}_{-0.01}$	$0.74^{+0.02}_{-0.03}$	$0.93^{+0.01}_{-0.02}$	$0.99^{+0.01}_{-0.01}$	$8.27^{+0.74}_{-0.69}$	$1.83^{+0.17}_{-0.09}$
HD 15337	5178^{+22}_{-21}	$4.53^{+0.01}_{-0.01}$	$0.25^{+0.01}_{-0.01}$	$0.73^{+0.02}_{-0.03}$	$0.90^{+0.02}_{-0.02}$	$0.85^{+0.01}_{-0.01}$	$7.51^{+1.09}_{-0.54}$	$1.73^{+0.03}_{-0.05}$
K2-291	5550^{+18}_{-14}	$4.50^{+0.01}_{-0.01}$	$0.06^{+0.01}_{-0.01}$	$1.03^{+0.01}_{-0.01}$	$0.92^{+0.02}_{-0.02}$	$0.89^{+0.01}_{-0.01}$	$6.13^{+1.43}_{-1.12}$	$1.57^{+0.07}_{-0.04}$
55 Cnc	5232^{+15}_{-15}	$4.40^{+0.01}_{-0.01}$	$0.45^{+0.01}_{-0.01}$	$0.81^{+0.01}_{-0.02}$	$0.92^{+0.01}_{-0.01}$	$1.00^{+0.01}_{-0.01}$	$8.09^{+0.40}_{-0.43}$	$2.00^{+0.21}_{-0.04}$
HD 80653	5901^{+32}_{-35}	$4.34^{+0.01}_{-0.01}$	$0.30^{+0.03}_{-0.01}$	$1.07^{+0.01}_{-0.01}$	$1.19^{+0.01}_{-0.02}$	$1.22^{+0.01}_{-0.01}$	$5.60^{+0.44}_{-0.33}$	$1.60^{+0.06}_{-0.04}$
K2-131	5054^{+12}_{-14}	$4.59^{+0.01}_{-0.01}$	$-0.08^{+0.01}_{-0.01}$	$1.15^{+0.01}_{-0.02}$	$0.83^{+0.01}_{-0.01}$	$0.76^{+0.01}_{-0.01}$	$6.82^{+1.54}_{-1.49}$	$1.74^{+0.20}_{-0.09}$
K2-229	5294^{+6}_{-6}	$4.58^{+0.01}_{-0.01}$	$0.20^{+0.01}_{-0.01}$	$0.52^{+0.01}_{-0.01}$	$0.89^{+0.01}_{-0.01}$	$0.80^{+0.01}_{-0.01}$	$2.71^{+0.43}_{-0.32}$	$1.25^{+0.11}_{-0.05}$
HD 136352	5764^{+20}_{-23}	$4.35^{+0.02}_{-0.01}$	$-0.29^{+0.02}_{-0.01}$	$1.02^{+0.01}_{-0.02}$	$0.88^{+0.03}_{-0.02}$	$1.03^{+0.01}_{-0.01}$	$4.69^{+0.34}_{-0.37}$	$1.62^{+0.03}_{-0.03}$
K2-38	5599^{+15}_{-15}	$4.33^{+0.01}_{-0.01}$	$0.18^{+0.01}_{-0.01}$	$0.95^{+0.01}_{-0.01}$	$1.02^{+0.01}_{-0.01}$	$1.15^{+0.01}_{-0.01}$	$11.68^{+3.26}_{-2.47}$	$1.59^{+0.12}_{-0.07}$
Kepler-10	5714^{+20}_{-20}	$4.33^{+0.01}_{-0.01}$	$-0.13^{+0.02}_{-0.01}$	$0.88^{+0.03}_{-0.01}$	$0.92^{+0.02}_{-0.02}$	$1.08^{+0.01}_{-0.01}$	$3.70^{+0.44}_{-0.37}$	$1.48^{+0.02}_{-0.02}$
Kepler-20	5486^{+17}_{-21}	$4.47^{+0.01}_{-0.01}$	$0.02^{+0.01}_{-0.01}$	$0.87^{+0.01}_{-0.03}$	$0.89^{+0.02}_{-0.02}$	$0.91^{+0.01}_{-0.01}$	$9.35^{+1.19}_{-1.65}$	$1.77^{+0.04}_{-0.02}$
Kepler-36	5989^{+19}_{-32}	$4.02^{+0.01}_{-0.01}$	$-0.23^{+0.03}_{-0.01}$	$1.32^{+0.01}_{-0.03}$	$1.09^{+0.02}_{-0.02}$	$1.70^{+0.01}_{-0.01}$	$3.65^{+0.11}_{-0.07}$	$1.55^{+0.05}_{-0.04}$
Kepler-93	5656^{+23}_{-25}	$4.44^{+0.01}_{-0.01}$	$-0.15^{+0.02}_{-0.01}$	$0.94^{+0.02}_{-0.03}$	$0.88^{+0.02}_{-0.02}$	$0.94^{+0.01}_{-0.01}$	$3.92^{+0.62}_{-0.49}$	$1.51^{+0.01}_{-0.01}$
Kepler-78	4980^{+16}_{-14}	$4.60^{+0.01}_{-0.01}$	$0.03^{+0.01}_{-0.01}$	$0.85^{+0.03}_{-0.02}$	$0.82^{+0.01}_{-0.01}$	$0.75^{+0.01}_{-0.01}$	$1.88^{+0.34}_{-0.29}$	$1.20^{+0.12}_{-0.08}$
Kepler-107	5928^{+23}_{-37}	$4.22^{+0.01}_{-0.01}$	$0.25^{+0.02}_{-0.01}$	$1.23^{+0.01}_{-0.02}$	$1.25^{+0.01}_{-0.01}$	$1.44^{+0.01}_{-0.01}$	$9.38^{+2.06}_{-1.54}$	$1.59^{+0.02}_{-0.02}$
WASP-47	5452^{+13}_{-16}	$4.32^{+0.01}_{-0.01}$	$0.42^{+0.01}_{-0.01}$	$0.98^{+0.01}_{-0.01}$	$1.03^{+0.01}_{-0.01}$	$1.16^{+0.01}_{-0.01}$	$6.75^{+0.56}_{-0.55}$	$1.85^{+0.02}_{-0.02}$
HD 213885	5889^{+20}_{-20}	$4.33^{+0.01}_{-0.01}$	$0.00^{+0.02}_{-0.01}$	$1.08^{+0.01}_{-0.01}$	$0.96^{+0.02}_{-0.02}$	$1.10^{+0.01}_{-0.01}$	$8.15^{+0.66}_{-0.62}$	$1.75^{+0.04}_{-0.05}$
K2-265	5405^{+8}_{-11}	$4.48^{+0.01}_{-0.01}$	$0.14^{+0.01}_{-0.01}$	$0.67^{+0.01}_{-0.02}$	$0.95^{+0.01}_{-0.01}$	$0.93^{+0.01}_{-0.01}$	$6.80^{+0.88}_{-0.95}$	$1.62^{+0.03}_{-0.04}$
HD 219134	4913^{+27}_{-32}	$4.58^{+0.01}_{-0.01}$	$0.22^{+0.03}_{-0.01}$	$0.64^{+0.03}_{-0.07}$	$0.80^{+0.02}_{-0.02}$	$0.76^{+0.01}_{-0.01}$	$4.70^{+0.14}_{-0.16}$	$1.57^{+0.01}_{-0.01}$
K2-141	4521^{+12}_{-11}	$4.62^{+0.01}_{-0.01}$	$0.29^{+0.02}_{-0.01}$	$0.45^{+0.04}_{-0.03}$	$0.79^{+0.01}_{-0.01}$	$0.72^{+0.01}_{-0.01}$	$5.53^{+0.30}_{-0.36}$	$1.59^{+0.04}_{-0.04}$

Table 1. Table containing all 20 stars in our sample, as well as their final inferred photospheric stellar parameters, stellar masses and radii, and planet masses and radii.



Planet Inferences

Figures 1 and 2. We inferred accurate, precise, homogenous, and self-consistent photospheric and fundamental stellar parameters **using a process that combines both the spectroscopy-only and the stellar isochrones approach**. Using these results and Doppler and transit observables, we can derive the strongest possible constraints on the masses and radii of the planets orbiting these stars. These figures compare the planetary masses and radii produced from our analysis and those based on the APOGEE DR17 and Brewer et al. (2016, 2018) catalogs. In both the mass and radius comparison, **we find no significant difference between results**, suggesting our spectroscopic approach produces consistent results regardless of the way that the photospheric stellar parameters are inferred.

Spectroscopic Analysis

The first part of the process involves a spectroscopic analysis. We used available spectroscopic data from various high-resolution, optical instruments to learn about the chemical structure of that star.

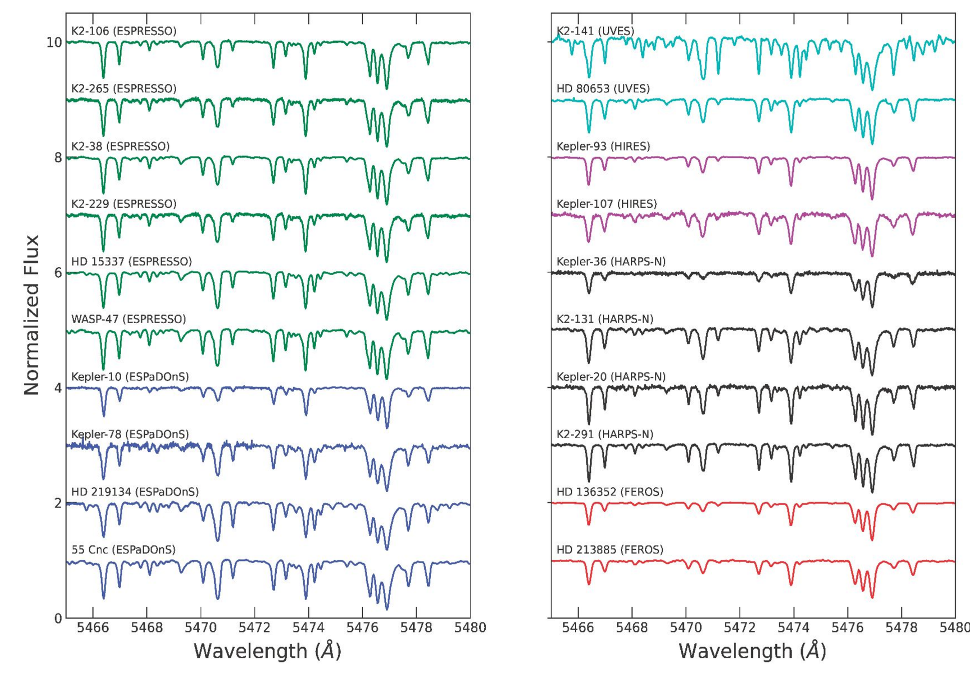


Figure 3. Comparison of normalized spectra between instruments, organized within each instrument by decreasing [Fe/H].

Using the python-based program *iSpec*, we fit Gaussian curves to known absorption lines of various elements and measure their equivalent widths (EWs), most importantly those of iron. We also measure oxygen, magnesium, silicon, calcium, and nickel EWs, elements that, with iron, together make up 97% of the Earth's bulk composition (and each comprise >1%).

Isochrones Posteriors

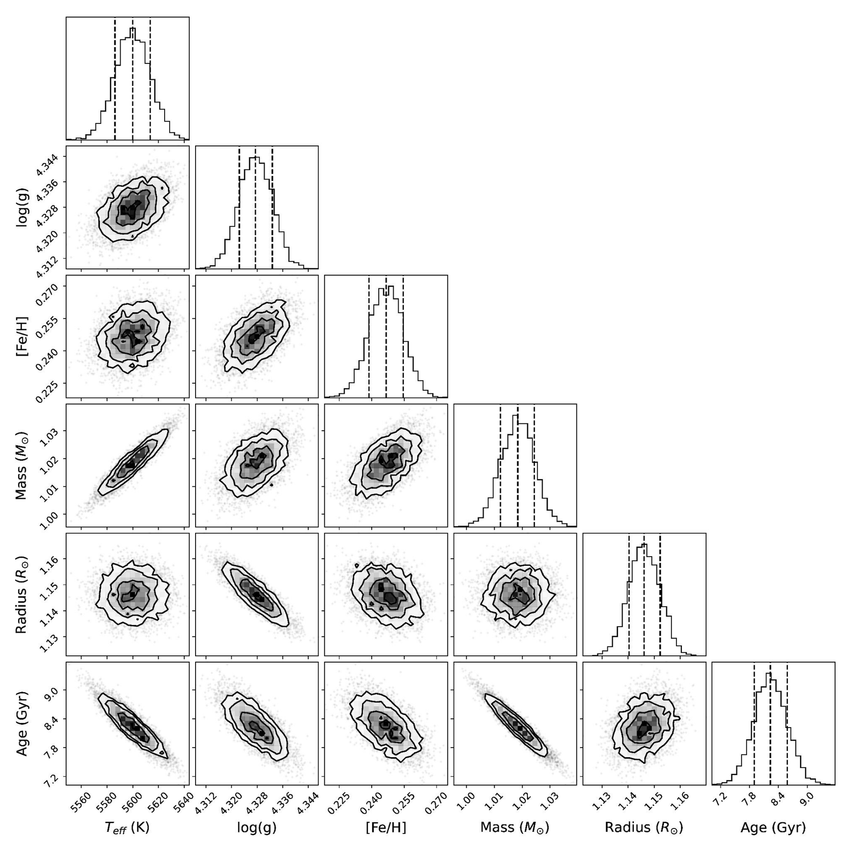


Figure 4. Corner plot for the physical parameters of star K2-38. This plots the 5422 posterior points produced by isochrones.

Using the results from the spectroscopic analysis, we can begin the next part of the process.

This part uses an algorithm that is summarized as follows:

1. Gather the EWs of iron lines from the spectroscopic analysis
2. With an initial guess of the temperature (Teff), surface gravity (logg), metallicity ([Fe/H]), and microturbulence (vt) of the star and the iron EWs, we use the python-based package *q2* to get a model atmosphere of stellar parameters.
3. Feed that result into the python-based package *isochrones*, which fits the model and accompanying photometric data onto stellar model grids (isochrones), giving us a posterior distribution of the star's inferred stellar parameters.

4. We repeat this process until the model [Fe/H] from *q2* and the inferred [Fe/H] from *isochrones* agree within their uncertainties.

5. Once they agree, we randomly sample 200 points from the *isochrones* posterior distribution, use *q2* to find a model atmosphere for each, and the resulting median is our result!