The GALAH Survey: Using Galactic Archaeology to Refine our Knowledge of TESS Target Stars

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ABSTRACT

An unprecedented number of exoplanets are being discovered by the Transiting Exoplanet Survey Satellite (TESS). Determining the orbital parameters of these exoplanets, and especially their mass and radius, will depend heavily upon the measured physical characteristics of their host stars. We have cross-matched spectroscopic, photometric, and astrometric data from GALAH Data Release 2, the TESS Input Catalog and Gaia Data Release 2, to create a curated, self-consistent catalog of physical and chemical properties for 47,285 stars. Using these data we have derived isochrone masses and radii that are precise to within 5%. We have revised the parameters of three confirmed, and twelve candidate, TESS planetary systems. These results cast doubt on whether CTOI-20125677 is indeed a planetary system since the revised planetary radii are now comparable to stellar sizes. Our GALAH-TESS catalog contains abundances for up to 23 elements. We have specifically analysed the molar ratios for C/O, Mg/Si, Fe/Si and Fe/Mg, to assist in determining the composition and structure of planets with \( R_p < 4 R_\oplus \). From these ratios, 36% fall within 2 sigma of the Sun/Earth values, suggesting that these stars may host rocky exoplanets with geological compositions similar to planets found within our own Solar system.

Key words: stars: abundances – planets and satellites: interiors – planets and satellites: terrestrial planet – methods: observational – astronomical data bases: catalogs

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1 INTRODUCTION

Exoplanets (planets that exist beyond the Solar system) moved beyond science fiction and into the realm of hard science late in the 20th century (Latham et al. 1989; Lawton & Wright 1989; Wolszczan & Frail 1992; Mayor & Queloz 1995). Over the first 18 years of the exoplanet era, radial velocity detections dominated exoplanet discovery, leading to a wealth of massive planet discoveries around largely Sun-like stars (e.g. Fischer et al. 2008; Vogt et al. 2010; Lovis et al. 2011; Wittenmyer et al. 2014; Endl et al. 2016).

Towards the end of the first decade of the 2000s, the transit technique became the numerically dominant method for making new exoplanet discoveries, and revealed an abundance of planets moving on very short period orbits (e.g. Noyes et al. 2008; Hellier et al. 2012; Muirhead et al. 2012; Rowe et al. 2014; Coughlin et al. 2016). The great advantage of transit observations over those using the radial velocity technique is that they permit surveys to target large numbers of stars simultaneously. The ultimate expression, to date, of the transit method as a tool for exoplanetary science came with the Kepler space telescope, launched in (2009) (Borucki et al. 2010).

At the time of writing, Kepler has been by far the most successful exoplanet detection program, discovering 65.5% of currently known exoplanets1. These planetary discoveries have showcased the vast richness and diversity of exoplanets across our galaxy. The great diversity of exoplanets and exoplanetary systems is illustrated by the discovery of large numbers of multi-planet systems (e.g. Gillon et al. 2017; Shallue & Vanderburg 2018), planets in extremely eccentric orbits (e.g. Naef, D. et al. 2001; Wittenmyer et al. 2017; Santerne et al. 2014), and planets that some have argued might resemble the Earth (e.g. Torres et al. 2015; Barclay et al. 2013).

The Kepler and K2 missions also revealed that planets larger than Earth, > 1R⊕, yet smaller than Neptune, < 4R⊕, are remarkably common – despite there being no such planets in the Solar system. Indeed, of those planets that we can readily detect, these “super-Earths” and “mini-Neptunes” seem to be by far the most common (Batalha et al. 2013). On 30 October 2018, the Kepler spacecraft depleted all of its on-board fuel, immediately retiring the mission and leaving behind a legacy that is unmatched in exoplanetary science. Fortunately, NASA’s Transiting Exoplanet Survey Satellite (TESS) mission, launched in April 2018, has picked up where the K2 mission left off.

The TESS mission (Ricker et al. 2014) is a space-based photometric survey that will cover the entire sky, except for the region within ±6 degrees of the ecliptic plane. The mission is designed to find small planets (Rp < 2.5R⊕) around nearby, bright, main sequence stars. As of 2020 August, there have been 66 confirmed planetary discoveries made as a result of TESS’ ongoing survey (e.g. Huang et al. 2018; Vanderspek et al. 2019; Nielsen et al. 2019b; Gilbert et al. 2020; Addison et al. 2020; Jordán et al. 2020). In addition to the 66 confirmed TESS exoplanets, there are more than two thousand TESS Targets of Interest (TOI)2 waiting for their exoplanetary status to be confirmed by ground-based teams (e.g Addison et al. 2019; Davis et al. 2019; Nielsen et al. 2019b; Wang et al. 2019a; Dalba et al. 2020; Eisner et al. 2020).

Once potential planets have been identified by TESS, the TESS Input Catalog (TIC) (Stassun et al. 2018; Stassun et al. 2019) and Candidate Target List (CTL) are the key catalogues that enable follow-up teams to characterise – for both stars and planets – the members of TESS candidate systems. In particular, radial velocity data are needed to measure the planetary mass, and spectroscopic observations are needed to refine mass and radius of the host star. These measurements, in combination with the transit radius measurement from TESS, allow the bulk density of the planet in question, ρp3, to be determined, and thereby provide constraints on that planet’s overall composition (Unterborn et al. 2016; Seager et al. 2007; Valencia et al. 2006).

Whilst the bulk density of a planet does provide clues to its potential bulk composition, it does not provide enough information for us to determine the geological structure of a potentially rocky planet, or to precisely determine its true composition. This is clearly illustrated by the work of Suissa et al. (2018), who demonstrate that a newly discovered “Earth-like” planet (a planet observed to be both the same mass and the same size as the Earth; i.e. 1M⊕, 1R⊕) could have a wide variety of internal compositions. Distinguishing between the many possible compositions and structures of such a planet will be of great interest in the years to come, particularly in the context of the search for potentially habitable planets, and the selection of the most promising such planets for further study (e.g. Horner & Jones 2010).

Recent studies, however, have demonstrated that planetary scientists could potentially unlock the viscera of distant rocky worlds by combining our knowledge of the planets themselves with detailed information on the chemical abundances of their host stars (e.g. Unterborn & Panero 2019; Dorn et al. 2019; Hinkel & Unterborn 2018; Unterborn et al. 2018a; Unterborn & Panero 2017; Dorn et al. 2017a; Unterborn et al. 2016; Dorn et al. 2015; Bond et al. 2010a). In particular, knowledge of the chemical abundances of refractory elements (such as Mg, Al, Si, Ca and Fe) and volatile elements (such as C and O) can help us to determine the likely structure and composition of exoplanets smaller than 4R⊕ (Dorn et al. 2019; Putirka & Ravich 2019).

The most crucial elements for such an analysis are C, O, Mg, Si, and Fe, as these elements will determine the core to mantle fraction (in particular Fe/Mg4) and the composition of a rocky exoplanet’s mantle (e.g. Mg/Si and C/O, as per Dorn et al. 2017a, 2015; Unterborn et al. 2014; Madhusudhan et al. 2012; Bond et al. 2010b). Such models have recently proven vital in inferring the geological and chemical composition of the planets in the TRAPPIST-1 (Unterborn

1 https://exoplanetarchive.ipac.caltech.edu/; accessed 6 August 2020.

2 https://exofop.ipac.caltech.edu/tess/; accessed 6 August 2020.

3 ρp = M_p / (4πR_p^3) : where M_p and R_p are the planet’s mass and radius, respectively.

4 Stellar abundance ratios are calculated by: (X) = 10^([X]/12+ΔY/X)⊥([X]/12+ΔY/X)
As the catalogue of known exoplanets has grown, it has become increasingly obvious that our understanding of the planets we find is often limited by the precision with which we can characterise their host stars. In particular, measurements of the elemental abundances of exoplanet host stars are becoming increasingly important in developing our understanding of the fundamental synergies between stars and the planets they host. As a result, there is an increasing amount of research within exoplanetary science that aims to understand the relationship between a star’s chemical abundances and the types of planets and planetary systems that they can form (e.g. Fischer & Valenti 2005; Adibekyan et al. 2012; Buchhave et al. 2014; Buchhave & Latham 2015; Teske et al. 2019).

The relationship between planetary demographics and a star’s measured photospheric iron abundance is a complex one. Over twenty years ago, studies showed that stars hosting hot-Jupiters (giant planets in very short period orbits) are typically iron-enriched compared to the Sun (Gonzalez 1997; Santos et al. 2001; Fischer & Valenti 2005). This trend has, however, weakened in more recent studies (Osborn & Bayliss 2019; Teske et al. 2019). Similarly, the relationship between a star’s iron abundance and the number of planets it hosts remains the subject of significant debate (e.g. Petigura et al. 2018; Adibekyan et al. 2017). Recent machine-learning work by Hinkel et al. (2019) has indicated that elemental abundances, including those of C, O, and Fe, can be used as a means to identify potential planet-hosting stars amongst the wider stellar population.

In addition to potentially helping us to understand the interior structure and composition of newly discovered exoplanets, recent work has also suggested that measurements of the elemental abundances of stellar photospheres and planetary atmospheres could also aid our investigation of the formation and migration history of the exoplanets we study. For example, Brewer et al. (2017) describe how measurements of an enhanced C/O ratio and [O/H] abundance in the atmospheres of ten hot Jupiters, compared to the equivalent abundances in their stellar hosts, serve as evidence that those planets must have formed beyond the water ice line, and that they must have then migrated inwards to reach their current location. In a similar fashion, studies of the composition and isotopic abundances of the planets and small bodies have long been used to attempt to disentangle their formation locations and migration histories (see e.g. Horner et al. 2020), and references therein). In summary, this recent work reveals that, if we are to fully characterise the exoplanets we discover, it is vital that we consider the elemental abundances of their host stars.

The southern hemisphere’s largest spectroscopic stellar abundance survey – the Galactic Archaeology with HERMES (GALAH) survey – is designed to investigate the stellar formation and chemical enrichment history of the Milky Way galaxy (De Silva et al. 2015; Martell et al. 2016; Buder et al. 2018). To do this, GALAH has collected high-resolution spectra for more than 600,000 stars, from which the abundances of up to 25 elements can be determined for each star. GALAH’s latest public release, GALAH DR2 (Buder et al. 2018), contains the details of 342,682 stars for which both physical and chemical properties have been observed and derived.

In this work, we make use of the data in GALAH DR2 to calculate revised values for the mass and radius of 47,285 stars that have been cross-matched between GALAH DR2 and the TIC. We then calculate the C/O, Fe/Mg and Mg/Si abundance ratios for those stars, providing a database of stellar abundances for potential planet hosting stars to facilitate future studies of the composition, structure, habitability, and migration history of exoplanets discovered by TESS.

In Section 2, we describe how GALAH DR2 is cross-matched with the TESS and Gaia catalogs (Section 2.1), before describing how we derive the isochronic stellar mass, radius and age estimates for our stars (Section 2.2). We then go on to discuss the derivation of elemental abundances and abundance ratios for GALAH-TESS stars using GALAH DR2 (Section 2.3). The resulting physical and elemental parameters are then validated by comparison with other catalogs in Sections 3.1 and 3.2. In our discussion section, we examine our refined stellar and planetary parameters for confirmed and candidate exoplanet host stars (Section 4.1) and the abundance ratio trends in our stellar sample (Section 4.2). Finally, we summarise our findings and draw our conclusions in Section 5.

2 METHODOLOGY AND DATA ANALYSIS

In this methodology section we describe how we cross-matched the GALAH-TESS catalog (Section 2.1), derived our physical stellar parameters including isochronic masses, radii and ages from GALAH DR2 (Section 2.2), and calculated our [X/H] and X/Y abundance ratios using GALAH DR2 data (Section 2.3).

2.1 Cross-matching the CTL and GALAH Catalogs

The TESS Input Catalog (TIC; Stassun et al. 2018; Stassun et al. 2019) presents the physical characteristics of stars that are likely to be observed during the primary TESS mission. Built before the launch of the spacecraft, the TIC uses photometric relationships to derive the physical properties of over 470 million point sources. Due to the large number of stars being observed by TESS, there is a selection process that gives a higher priority to stars that better suit the TESS mission goals, which are primarily to discover planets around bright, cool dwarfs (Ricker et al. 2014; Stassun et al. 2018). Stars within this subset of the TIC are a large component of the Candidate Target List (CTL), and are observed by TESS at a two-minute cadence, whilst the remaining targets are recorded at a 30-minute cadence in the full-frame images (FFIs).

Several simulations of the exoplanetary outcomes of TESS have been produced, including Sullivan et al. (2015) and Barclay et al. (2018). Sullivan et al. (2015) predicted that TESS will discover 20,000 planets over the next two years (1,700 from CTLs and the rest from full-frame images). A more conservative yield prediction by Barclay et al. (2018) estimates that 1,250 exoplanets will be discovered orbiting CTL stars, with an additional 3,100 being found orbiting...
stars within the full-frame images. Both sets of simulations suggest that a large number of planets will discovered by TESS, from both the CTL and full TIC samples.

The most recent data release from GALAH (DR2; Buder et al. 2018) contains data derived from high resolution spectra for a total of 342,682 southern stars. Stars in the GALAH DR2 were first cross-matched with Gaia’s second data release (DR2; Gaia Collaboration et al. 2018), using the TOPCAT (Taylor 2005) tool to match GALAH and Gaia sources with a position tolerance of ±1”, providing Gaia-band magnitudes and parallaxes for our isochronic models. The returned stars were then cross-matched against release 8.0 of the TIC5 using 2MASS (Skrutskie et al. 2006) identifiers from the GALAH catalog, accessed through the Mikulski Archive for Space Telescopes astroquery’s API (Ginsburg et al. 2019).

For our catalog, we selected GALAH DR2 stars with a high signal-to-noise (S/N) across all four of HERMES’s CCDs, only accepting stars that had a S/N ratio value of 50 or higher in each wavelength band. We also omit stars with a flag_cannon greater than zero, which indicates some problem in the data analysis, from our data set. The flagging scheme utilised in GALAH DR2 is described in greater detail in Buder et al. (2018).

For completeness, we compared the Gaia G band magnitude from the TOPCAT cross-match to the same value found in the CTL catalog. These values should be identical to one another, and hence serve as confirmation that we have the correct stars cross-matched within our catalog. We considered a match to be confirmed if the difference in a star’s celestial coordinates was less than 0.0001 degrees and the difference in 2MASS J-H colour magnitudes (J-H) was also below 0.0001 mag for the exoplanet hosts.

We also wanted to include in our GALAH-TESS sample any stars that may have slightly lower S/N spectra in GALAH, but which are known to host either a confirmed exoplanet, a TESS TOI, or a CTOI. We accessed the TESS Follow-up Observing Program and NASA’s EXOPOP-TESS databases, and cross matched them with GALAH DR2 and Gaia DR2. Our cross-match approach was simpler for these targets, as we merely needed to match them by their TIC IDs.

Taking all of the above into consideration, our newly formed GALAH-TESS catalog boasts 47,285 stars across the southern night sky, as shown in Figure 1. Of these 47,285 stars, 2,260 are prioritised sufficiently highly by the TESS mission that they are included in the TIC’s CTL catalog, being observed with a higher cadence relative to other stars in the general TIC. Figure 2 shows the distributions of our GALAH-TESS stars as a function of their TESS and V-band magnitudes. The median TESS magnitudes for our CTL and TIC stars are 11.4 and 12.5, respectively, whilst the median V-band magnitudes for our CTL and TIC stars are 10.7 and 11.9 respectively. The slightly lower median values for stars on the CTL compared to those for the general TIC reflect TESS’s primary mission objectives, prioritising brighter stars.

Due to flexible constraints by which we cross-matched the catalogs, there are GALAH-TESS stars that are located within the ecliptic, with a TESS priority of zero, that will not be observed within the initial two year TESS primary mission. We have left those stars in our GALAH-TESS catalog, as they might be observed during the extended mission, following the conclusion of the primary survey. There is a large, deliberate absence of stars surrounding the TESS Continuous Viewing Zone, with no star within our catalog being found at ecliptic latitudes south of -78°, in order to avoid any crossover of stars being observed and analysed by the TESS-HERMES Survey (Sharma et al. 2018). There are also no stars in our catalog which overlap fields observed as part of the K2 survey, in order to avoid any potential crossover with the K2-HERMES survey (Wittenmyer et al. 2018; Sharma et al. 2019).

5 https://filtergraph.com/tess_ctl; accessed 6 August 2020.
Figure 2. Of the 47,285 stars that are included in both the GALAH DR2 catalog and the TESS input catalog (TIC), 2,260 are members of the Candidate Target List (CTL; shown here in purple), and are scheduled to be observed with a higher cadence relative to stars within the general TIC (orange). Left: Of the 2,260 CTL stars, 650 stars are brighter than a TESS magnitude ($T_{mag}$) of 10, 1527 lie between between $T_{mag}$ 10–12, and 83 with a $T_{mag}$ between 12–14. The median TESS magnitudes for our CTL and TIC stars are 11.4 and 12.5 respectively. The top plot shows the number of TIC and CTL members in each bin whilst the bottom plot shows the percentage of stars in each magnitude bin that belong to the TIC and CTL, respectively. Right: Of the 2,260 CTL stars, 299 stars are brighter than a V magnitude of 10, 1099 lie between V magnitudes of 10–12, and 862 have a V magnitude between 12–14. The median V magnitudes for our CTL and TIC stars are 10.7 and 11.9, respectively. The slightly lower median values for CTL values compared to the TIC reflect TESS’s primary mission objectives, prioritising brighter stars. The significant increase in the number of stars between Vmag 12.0–13.7 and $T_{mag}$ 11.3–13.0 reflects GALAH’s observing strategy.

2.2 Deriving Stellar Radii, Masses and Ages from GALAH Stellar Parameters

Details on the observation strategy and data pipeline for GALAH DR2 can be found in Kos et al. (2017); Martell et al. (2016) and Buder et al. (2018). Briefly, all GALAH DR2 observations are acquired with the 3.9 metre Anglo-Australian Telescope situated at the Siding Spring Observatory, Australia. The two degree-field prime focus top-end (2dF; Lewis et al. 2002) with 392 science fibres is used to feed the High Efficiency and Resolution Multi Element Spectrograph (HERMES) (Sheinis et al. 2015), delivering high resolution (R $\approx$28,000) spectra in four wavelength arms covering 471.3-490.3 nm, 564.8-587.3 nm, 647.8-673.7 nm and 758.5-788.7 nm.

The spectra for each star are corrected for systematic and atmospheric effects and then continuum normalised. Detailed atmospheric parameters, including effective temperature ($T_{eff}$), surface gravity (log g), global metallicity ([M/H]), and individual abundances ([X/Fe]), have been determined for 10,605 selected stars using 1D stellar atmospheric models via the Spectroscopy Made Easy (Valenti & Piskunov 1996) package. Both the spectroscopic information and stellar parameters for these 10,605 stars then form a training set for the machine-learning algorithm The Cannon (Ness et al. 2015), which is used to train a data driven spectrum model algorithm on the entire GALAH DR2 survey. Flags are produced by The Cannon’s processing for the “quality” of the derived physical parameters in each star. For our analysis, we only include stars in the GALAH-TESS catalog if they have a “0” flag_cannon in the GALAH DR2 release.

To derive the mass, radius, and ages of our GALAH-TESS stars, we used the Python package isochrones (Morton 2015). The isochrones code uses MESA Isochrones & Stellar Tracks (MIST) (Choi et al. 2016) stellar evolution grids to infer the physical characteristics of stars. For this analysis, we used as input observables: the star’s effec-
The effective temperature ($T_{\text{eff}}$), surface gravity ($\log g$), 2MASS ($J$, $H$, $K_s$) and Gaia ($G$, $G_{\text{RP}}$, $G_{\text{BP}}$) photometric magnitudes, along with parallax values obtained by Gaia DR2 (Gaia Collaboration et al. 2018) where available. Isochrone models rely on knowledge of a star’s global metallicity, [M/H]. The assumption that the iron abundance [Fe/H] can be a proxy (or even equal) to [M/H] breaks down for metal-poor stars (e.g. Recio-Blanco et al. 2014; Adibekyan et al. 2013, 2012; Reddy et al. 2006; Fuhrmann 1998). The radiative opacity of metal poor-stars can be heavily affected by Mg, Si, Ca and Ti (i.e. by $\alpha$-elements). Including these $\alpha$-elements in our calculations of global metallicity better predicts the physical parameters derived with isochrones. GALAH DR2 calculates an [$\alpha$/Fe] value for each star using Equation 1:

$$[\alpha/\text{Fe}] = \frac{\sum (X/\text{Fe})}{\sum (e_{\text{X}}[X/\text{Fe}])^{-2}}$$

where $X =$ Mg, Si, Ca, and Ti and $e_{\text{X}}[X/\text{Fe}]$ is the abundance’s associated uncertainty. [$\alpha$/Fe] will be calculated even if one or more of these elements are missing. From our iron abundance, [Fe/H], and [$\alpha$/Fe], we can then calculate [M/H] using Salaris et al. (1993):

$$[\text{M/H}] = \text{[Fe/H]} + \log_{10} (0.638f_\alpha + 0.362).$$

where $f_\alpha$ is the $\alpha$-element enhancement factor given by $f_\alpha = 10^{f_{\alpha}/2}$. Our calculated [M/H] value is then used in the isochrone modelling of each star.

When using isochrones, if a star failed to converge, it was omitted from our catalog. Of our original 47,993 stars, 708 stars failed to converge, leaving the 47,285 stars that comprise the GALAH-TESS catalog. When the model reached convergence, the median output values of the stellar mass, radius, density, age, and equivalent evolution phase, as well as their corresponding 1-$\sigma$ uncertainties are calculated from the posterior distributions. We calculate stellar luminosity through the Stefan-Boltzmann relationship, and use those luminosities to derive the habitable zone boundaries for each star, as formulated by Kopparapu et al. (2013). GALAH DR2 rotational, radial and microturbulence velocities have been included in the GALAH-TESS catalog to assist ground-based radial velocity teams to better prioritise follow-up targets.
Figure 4. Comparing GALAH’s global metallicity [M/H] to that of the TIC, with the colour of each star colour denoting its surface gravity, as derived by GALAH. The median error-bar is given by the grey point to the Figure’s top-left corner, with an equality line given by the dark grey dashed line. The TIC directly uses GALAH DR2’s [Fe/H] as [M/H], which this equality holds for thin-disc and alpha-poor stars. However, for thick-disc and alpha-rich stars, this equality does not hold true. From this figure, the median difference between [M/H] and [Fe/H] for alpha-rich stars is \(-0.3\) dex. Since isochronic evolutionary tracks depend on [M/H], this assumption of [M/H] = [Fe/H] would have given less accurate mass, radius, and age results for our alpha-rich stars. For a small portion of our stars, there was no [\alpha/Fe] abundance, and hence we use [Fe/H] as [M/H] in our isochrone models for these specific stars.

2.3 Deriving Stellar Abundances and Ratios for GALAH-TESS stars

In addition to providing the physical parameters for over 47,000 stars, our catalog also contains the chemical parameters that could prove vital in determining the composition of rocky planets potentially hosted by these stars. Stellar elemental abundances for 23 elements, as well as quality flags, are derived from The Cannon, with the details of the derivation of these abundances their associated systematics discussed in detail in Buder et al. (2018). To ensure that we deliver to the community a usable catalog, we have removed values with [X/Fe] flags not equal to zero.

Whilst GALAH DR2 has its own internal Solar normalisation, we have converted our elemental abundances from a GALAH normalised scale to Lodders et al. (2009) Solar normalisations, where available.

3 RESULTS

Our results section is split into two separate parts, which detail the in-depth results of both the physical (Section 3.1) and chemical (Section 3.2) characteristics of stars within our GALAH-TESS catalog, and provide comparisons of those results to other surveys and catalogs.

3.1 Physical Stellar Parameters

The current TIC incorporates data from large, ground-based spectral surveys including LAMOST (Cui et al. 2012), RAVE (Steinmetz et al. 2006), TESS-HERMES (Sharma et al. 2018), and GALAH. For the vast majority of stars in our sample, the TIC has incorporated GALAH DR2 effective temperatures, which can be seen as a line of equality in Figure 3. Our GALAH-TESS temperatures, which have a median error of 54 K, seem to be in reasonable agreement with Gaia’s, with a larger scatter for hotter stars than for cooler stars.

There tends to be a slightly better agreement with Gaia’s Teff for stars slightly cooler than the Sun (4750 \(\leq\) GALAH-TESS Teff \(\leq\) 5500) with an RMS of 146 K and median bias of 50 K, compared to the hotter stars, (Teff > 5500), and cooler stars, (Teff < 4750), with RMS values of 168 K and 253 K and median bias values of 34 K and 25 K, respectively. The high scatter in results for the hotter stars is to be expected, with (Buder et al. 2018) noting an underestimate of GALAH Teff values for hotter Gaia benchmark stars, which might be due to GALAH’s input training set preferentially favouring cooler temperatures. There are horizontal structures between 5250–5750 K for Gaia Teff values compared to those obtained using GALAH data. Similar structures were found by Hardegree-Ullman et al. (2020) when comparing Gaia Teff values with spectral values obtained with LAMOST. These structures suggest that the Gaia temperature calculations in this range tend to certain preferred temperatures, which may be the result of Gaia’s input training set.

Because the TIC prioritises stars being observed with a two-minute cadence (the CTL), surface gravities are only presented within the TIC for dwarf stars with a log g > 3. In addition, the TIC does not include include derived log g values from other surveys, opting instead for a homogeneous dataset to ensure internal consistency with their mass and radius values. In our cross-matched sample, we include both dwarfs and giants, since giant stars are also known to be planet-hosts (Johnson et al. 2011; Jones et al. 2016; Huber et al. 2019; Wittenmyer et al. 2020). As a result, Figure 3 only shows the comparison for GALAH-TESS stars that have both measured log g values in both catalogs. For our sample of dwarfs that have TIC log g values, the agreement Fe/Mg and C/O ratios were all calculated\(^6\) using our [X/H] stellar abundances and Lodders et al. (2009) Solar normalisations, where available.

\(^6\) Stellar abundance ratios, also known as stellar molar ratios, are calculated by:

\[
\frac{X}{Y} = 10\left(\frac{\text{[X/H]}}{\text{[Y/H]}}\right)_{\odot}^{\text{[X/H]}} - 10\left(\frac{\text{[Y/H]}}{\text{[Y/H]}}\right)_{\odot}^{\text{[Y/H]}}
\]
between their log g values and ours appears reasonable, with an RMS and median bias of 0.14 and -0.03 dex respectively compared to the median GALAH log g error of 0.16 dex.

The TIC’s global metallicity values, [M/H], have mostly been acquired from the large, ground-based surveys such as LAMOST, RAVE, etc. (Cui et al. 2012; Steinmetz et al. 2006). For those stars for which the TIC used GALAH DR2 parameters, they incorrectly assumed that the iron abundance, [Fe/H] is equal to the star’s global metallicity, [M/H]. However, there is a large discrepancy between [M/H] and [Fe/H] for thick-disk and metal-poor stars that are enriched in α-elements. These α-elements affect the radiative opacity of iron-poor stellar surfaces, with the result that the overall metallicity and iron abundance equality breaks down. If the overall metallicity does not take into account the α-abundance, [α/Fe], for iron-poor stars, this could drastically alter the star’s derived isochrone track. This in turn would alter the final stellar parameters that are produced with this model.

If we wish to better characterise stars observed with TESS, we therefore need to take [α/Fe] into consideration, as we did in Section 2.2. Figure 4 shows the comparison between the overall metallicities taken from the TIC, and those calculated using GALAH data. There are 317 stars that do not have a [α/Fe] measurement, and for those stars, we simply equated their iron abundance to the overall stellar metallicity. The RMS and bias between the TIC and GALAH’s overall metallicity is 0.18 and 0.08 dex respectively. As we expected, however, the RMS between the two datasets is significantly lower for alpha-poor stars ([α/Fe] < 0.1), with an RMS and bias values being 0.08 and 0.05 dex respectively. There is a much larger difference in [M/H] for iron-poor/alpha-rich stars, which is to be expected, with a RMS and bias of 0.32 and 0.27 dex respectively. For comparison, the median error in the derived [M/H] values is 0.07 dex.

GALAH’s T eff, log g and [M/H] values together with the astrometric and photometric observables are fed into the isochrones code, producing the radius and mass values which are depicted in Figure 5. Our radii show good overall agreement with both Gaia DR2 and TIC. However, at large radii (giant stars), our calculated radii tend to be smaller than those taken from the TIC and Gaia. The median relative error for our stellar radii is 2.7%, with the relative RMS between our results and those of Gaia DR2 and TIC found to be 10% and 14%, respectively. Our median stellar radius value is 1.89 R⊙, which is comparable to the median values of the Gaia and TIC data of 1.84 R⊙ and 1.92 R⊙, respectively.

The general agreement between our results and the radii derived by Gaia and the TIC is not unexpected, since our isochrones models rely on Gaia DR2’s photometric magnitudes and parallax values. The TIC’s methodology is similar in that it also relies on data from Gaia to derive its stellar.

Figure 5. Left: Comparing the stellar radii of GALAH-TESS stars with the TIC (blue) and Gaia (pink). There is good overall agreement between the derived radius values, with a relative RMS of 10% and 14% for Gaia DR2 and TIC values respectively. An equality line is present in both plots, in the form of the dark grey dashed line. Right: Comparing our GALAH-TESS stellar masses with TIC-derived stellar masses. There is a good overall agreement between the derived isochrone masses and the TICs, with an RMS of 0.12 M⊙. Only dwarf stars within the TIC have mass measurements, and thus these comparisons are only valid for this luminosity class. Each star is coloured by its stellar radius, with median error bars given in the bottom-right corner.
Figure 6. A Hertzsprung-Russell diagram of our GALAH-TESS cataloged luminosity using GALAH DR2’s $T_{\text{eff}}$ and our isochrone-derived luminosity values. Stars selected for our catalog include both those on the main sequence (lower right to mid-left; high log g) and evolved stars (mid-left to upper left; low log g). We have included giant stars within our catalog as these stars are also known to host exoplanets, and it seems likely that analysis of TESS’s full frame images will yield a number of new discoveries of this type.

Our distribution between selected elements and the measured abundances. Generally our catalog median values are near Solar, with C, O, Al, K, and Fe median values being significantly sub-Solar, and Li, Co, Y and La being significantly super-Solar (though Li suffers from small number statistics). It is not possible, however, to provide accurate elemental abundances for all 23 elements for all of our target stars – and so we have only provided abundances for those species which can be reliably determined from each star’s spectrum. As a result, 90% of our sample have reliable O, Si, Mg, Si, Zn, and Y abundances, whilst just 2% of the stars cataloged yield reliable Co abundances. In the most extreme case, only 23 stars in our catalog have reliable, measured Li abundances. Generally our catalog median values are near Solar, with C, O, Al, K, and Fe median values being significantly sub-Solar, and Li, Co, Y and La being significantly super-Solar (though Li suffers from small number statistics).

Our distribution between selected elements and the measured abundance. The paucity of stars with a reliable Li abundance is particularly apparent.

Table 1. Here, we present the median and 1σ error values for $[X/H]$ abundances derived in our GALAH-TESS catalog normalised by Lodders et al. (2009). We also give, in the second column, the number of stars in our catalog for which a reliable value for the abundance in question was obtained. The 1σ error values here quoted are the median 1σ error values for each elemental abundance. The paucity of stars with a reliable Li abundance is particularly apparent.

number of cool dwarf stars is consistent with GALAH being a magnitude-limited survey and the TESS goals of detecting exoplanets primarily around bright, nearby stars.

3.2 Chemical Stellar Parameters

Our catalog of ~47,000 stars provides elemental abundances for up to 23 unique species derived from GALAH DR2 abundances. It is not possible, however, to provide accurate elemental abundances for all 23 elements for all of our target stars – and so we have only provided abundances for those species which can be reliably determined from each star’s spectrum. As a result, 90% of our sample have reliable O, Si, Mg, Si, Zn, and Y abundances, whilst just 2% of the stars cataloged yield reliable Co abundances. In the most extreme case, only 23 stars in our catalog have reliable, measured Li abundances. Generally our catalog median values are near Solar, with C, O, Al, K, and Fe median values being significantly sub-Solar, and Li, Co, Y and La being significantly super-Solar (though Li suffers from small number statistics). Our distribution between selected elements and the measured Fe abundance is shown in Figure 7. Given the paucity of Li measurements, we do not discuss the abundances of that element further in this work.

To validate our stellar abundances, we made use of the online, interactive stellar abundance catalog, the Hypatia Catalog Hinkel & Burger (2017a). The Hypatia Catalog is an amalgamation of stellar abundances, including physical and planerary parameters, for stars within 150 pc of the Sun (Hinkel et al. 2014, 2016; Hinkel & Burger 2017b). Comprised of mostly FGKM-type stars, the catalog is compiled from more than 190 literature sources that can be normalised by several Solar normalisations, particularly Lodders et al.

Footnote 7: We direct the interested reader to Martell et al. (2020), and references therein, for a discussion of Li abundances from GALAH data, with a particular focus on the mechanisms by which different populations of stars can end up with dramatically different Li distributions.
Figure 7. 2-D histogram distributions of elemental abundances versus iron abundance for planet-building lithophile (Lith), siderophile (Sid) and volatile (Vol) elements. The Sun’s values are represented on each plot by a white-bordered, hollow star, with the median values depicted by triangles. Since there are some elements that are easier to detect in a stellar photosphere than others, each bin is coloured by the fraction of the maximum bin value in each plot. The maximum bin value for each plot is given in the plot’s top right-hand corner.

By using the Hypatia Catalog alongside the abundances within our sample, we can directly compare our abundances that use the same Solar normalisation. We accessed the Hypatia Catalog on 6 August 2020 and cross-matched our GALAH-TESS stars with stars within Hypatia by directly comparing their 2MASS identifiers.

Our GALAH-TESS catalog contains data for 606 stars that are within 150 pc of the Sun, of which five matched with the Hypatia Catalog. Figure 8 shows the comparison of elemental abundances for the five cross-matched stars, namely HD 121004, HD 138799, HD 139536, HD 89920 and HD 103197. HD 121004 is the only metal-poor star within our sample that was cross-matched with Hypatia, with the other four stars boasting super-Solar abundances. HD 121004, a G2V dwarf, has elemental abundances that show the best agreement with the abundances within Hypatia, with a median difference of 0.03 dex with those nine specific elements. The four iron-rich stars, which are all K dwarfs, show a minor discrepancy between their elemental abundances, with the GALAH abundances being enriched by 0.12 - 0.14 dex compared to Hypatia.

In terms of the abundance difference per element between our data and those presented in the Hypatia catalog, the Ti abundances agree to within a median value of 0.03 dex, which is within the median 1-σ error of GALAH-TESS and Hypatia Ti abundances for this sample, being 0.03 and 0.05 dex, respectively. The values for Ca, Al, and Na between the two catalogs differ by 0.08 dex, with the Fe, O, Si, and Ni abundances varying between the catalogs by between 0.12 and 0.16 dex. The largest discrepancy between abundances comes from Mg, which are overabundant in GALAH by 0.30 dex. The GALAH DR2 abundances include non Local Thermodynamic Equilibrium (non-LTE) effects for O (Amarsi et al. 2016a), Na, Mg (Osorio et al. 2015; Osorio & Barklem 2016), Al, Si (Amarsi & Asplund 2017), and Fe (Amarsi et al. 2016b) (Buder et al. 2018; Gao et al. 2018), whereas the Hypatia abundances (from Adibekyan et al. 2012) do not take into account non-LTE affects, which may explain the...
discrepancy between the difference in elemental abundance values.

We calculated the Mg/Si, Fe/Mg, Fe/Mg and C/O abundance ratios using our GALAH-TESS [X/H] values and Solar values from (Lodders et al. 2009). We only returned a ratio value if stars had both elements available to us, with 43,162 Fe/Si, 44,968 Fe/Mg, 41,741 Mg/Si and 9,521 C/O abundance measurements available. The limited C/O ratio measurements reflect the one atomic C line and two O lines available for reliable abundance measurements across HERMES' wavelength coverage and resulting detection limits. The median and 1σ error values for our selected GALAH-TESS abundance ratios are presented in Table 2. For reference, the Solar values for Fe/Si, Fe/Mg, Mg/Si and C/O using Lodders et al. (2009) are 0.85, 0.81, 1.05 and 0.46, respectively. Our abundance ratios all tend to have sub-Solar Fe/Si, Fe/Mg, Mg/Si and C/O ratios. The distribution of our C/O and Mg/Si values are plotted against each other in Figure 13, and are discussed in more detail in Section 4.2.

Stellar elemental abundances can change slightly, depending upon the Solar normalisation used to derive such abundances. To illustrate this, we have then created Figure 9 to show the distribution of our [X/H] abundances for planet-building elements scaled to the various Solar normalisations that are widely used within exoplanetary science. These rocky-planet building elements include the volatiles, which typically reside in the atmosphere (C, O), the lithophiles, which are present in the crust/mantle of rocky planets (Na, Mg, Al, Si Ca, Sc, Ti, V, Mn, Y), and the siderophiles, which easily alloy with Fe and primarily reside in the core (Cr, Fe, Co, Ni) (Hinkel et al. 2019). Having six different normalisations means that each star in the sample is counted six times. However, this allows the skewed distributions from the different methods to be assessed in a single figure, and forms the basis for Figure 9, where we present the skews for all sixteen planet-building elements.

From Figure 9, it is readily apparent that there is general overall agreement among our abundances normalised by (Lodders et al. 2009), when compared to other distributions with the total median of the distributions falling within 1-σ of our L09 values. Volatile elements such as C and O and lithophiles Na and Mg tend to negative [X/H] values in older normalisations compared to newer normalisations that instead peak towards super-Solar values. Larger changes can be seen in the spread of median C/O, Mg/Si and Fe/Mg abundance ratios for these different Solar normalisations. The spread of our median C/O values vary from 0.44 to 0.64, from 0.98 to 1.35 for Mg/Si, and from 0.58 to 1.39 for Fe/Mg depending upon what Solar normalisation is used. Changing the value of Mg/Si for a given planet would have the primary effect of altering the mantle mineralogy between olivine-rich and pyroxene-rich (Hinkel & Unterborn 2018; Unterborn & Panero 2017; Brewer & Fischer 2016; Thiabaud et al. 2014a, 2015). These differences in composition are known to change the degree of melting and crustal composition (Brugman et al. 2020), but the degree that that composition changes the interior behavior of a rocky exoplanet remains an area of active research. These results therefore highlight the importance of normalising abundances to the same Solar normalisations when comparing chemical abundances from different surveys and considering the implications those results might have on inferring the structure of rocky exoplanets.

4 DISCUSSION

In this section we discuss the refinement of planetary systems with the newly derived GALAH-TESS stellar parame-
Figure 9. The same distribution of planet-building elements as found in Figure 7. Here, however, we have normalised our \([X/H]\) values to various Solar normalisations including Asplund et al. (2009); Lodders et al. (2009); Grevesse et al. (2007); Asplund et al. (2005); Grevesse & Sauval (1998); Anders & Grevesse (1989), displayed in yellow, orange, pink, purple, violet and navy respectively. Combining the stellar abundances in this manner with different Solar normalisations shows the general trends within a certain element, unbiased by using a specific Solar normalisation.

| Num. of stars | (X/Y) | \((X/Y)_S\) |
|---------------|-------|-------------|
| Fe/Si         | 43162 | 0.65 ± 0.22 | 0.85 |
| Fe/Mg         | 44968 | 0.68 ± 0.23 | 0.81 |
| Mg/Si         | 41741 | 0.98 ± 0.22 | 1.05 |
| C/O           | 9521  | 0.44 ± 0.13 | 0.65 |

\(^*\) Solar values from Lodders et al. (2009).

Table 2. Median and 1σ error values for our GALAH-TESS abundance ratios. The majority of our stars have Mg/Si, Fe/Mg, and Fe/Mg values, however only 20% have reliable C/O measurements.

4.1 Refining Planetary System Parameters

Within our GALAH-TESS sample, we cross-matched our GALAH-TESS sample with the catalog of known planetary systems on NASA’s Exoplanet Archive and TOIs or CTOIs by accessing the Exoplanet Follow-up Observing Program for TESS (ExOFOP-TESS)\(^9\) website. At the time of writing, the GALAH-TESS catalog contains three confirmed single-planet systems: WASP-61 (Smith et al. 2012), WASP-182 (Nielsen et al. 2019a) and HD 103197 (Mordasini et al. 2011). Our catalog also includes five single-planet candidate systems namely TOI-745, TOI-815, TOI-1031, TOI-777 and TOI-1126. We should note that WASP-61 b is also known as TOI 439.01. Lastly, there are also three CTOI planetary systems, two of which host two candidates, TIC 201256771 and TIC 1126. The other CTOI system is a three-planet candidate system, TIC 300903537. A brief summary of the revised stellar parameters for these 11 confirmed and candidate exoplanet hosts are summarised in Table 3.

The calculated radius of an exoplanet planet is directly related to the radius of its host star - so any change in stellar radius will change the radius of the planet. All of our exoplanets and candidates have transit depth measurements from TESS, which we obtain from ExOFOP-TESS,

\(^9\) https://exofop.ipac.caltech.edu/; accessed 6 August 2020.
Table 3. Our stellar physical parameters of matched confirmed and candidate exoplanet hosts. For CTOI hosts, since their CTOI ID is simply their TIC ID, we have omitted this column from the table. [M/H] in this table is the overall metallicity and not the host star’s iron abundance, [Fe/H].

| Catalog ID | TOI ID | TIC ID | $T_{\text{eff}}$ | [M/H] | log g | $M_*$ | $R_*$ |
|------------|--------|--------|-----------------|-------|-------|-------|-------|
| WASP-61    | 439    | 13021029 | 6245 ± 58      | -0.06 ± 0.08 | 4.03 ± 0.17 | 1.29 ± 0.03 | 1.38 ± 0.02 |
| UCAC4 238-060232 | 754    | 72985822 | 6096 ± 59 | 0.13 ± 0.08 | 4.16 ± 0.17 | 1.16 ± 0.04 | 1.21 ± 0.03 |
| CD-43 6219 | 815    | 102840239 | 4954 ± 34 | 0.13 ± 0.05 | 4.46 ± 0.11 | 0.83 ± 0.01 | 0.76 ± 0.01 |
| UNSW-V 320 | 201256771 | 4979 ± 50 | 0.04 ± 0.07 | 3.42 ± 0.15 | 1.29 ± 0.09 | 3.22 ± 0.07 |
| CD-57 956 | 220402280 | 5817 ± 41 | 0.08 ± 0.06 | 4.33 ± 0.13 | 1.04 ± 0.03 | 1.10 ± 0.01 |
| UCAC4 306-282520 | 300083537 | 4841 ± 83 | 0.2 ± 0.09 | 4.41 ± 0.19 | 0.82 ± 0.02 | 0.80 ± 0.01 |
| HD 81655 | 1031    | 304021498 | 6415 ± 44 | -0.19 ± 0.06 | 3.88 ± 0.14 | 1.32 ± 0.04 | 1.89 ± 0.02 |
| HD 106100 | 777    | 334305570 | 6187 ± 35 | 0.12 ± 0.05 | 3.82 ± 0.11 | 1.28 ± 0.02 | 1.54 ± 0.02 |
| WASP-182 | 369455629 | 5615 ± 50 | 0.32 ± 0.07 | 4.15 ± 0.15 | 1.05 ± 0.03 | 1.25 ± 0.02 |
| HD 103197 | 400806831 | 5223 ± 32 | 0.35 ± 0.04 | 4.43 ± 0.11 | 0.94 ± 0.02 | 0.90 ± 0.01 |
| TYC 7914-01572-1 | 1126 | 405862830 | 5108 ± 55 | 0.09 ± 0.08 | 4.66 ± 0.17 | 0.82 ± 0.02 | 0.74 ± 0.01 |

except for WASP-182 b and HD 103197 b. For the short-period transiting exoplanet WASP-182 b, there is currently no transit data from TESS. Instead we use the transit depth values from its discovery paper (Nielsen et al. 2019a) to refine its radius. Unfortunately, at the time of writing, the longer-period exoplanet HD 103197 b has not been observed to transit its host, and no direct size determination is possible.

A brief summary of the revised planetary radii for the 14 confirmed and candidate exoplanets are summarised in Table 4 along with the transit depth and literature planetary radii against which we are able to compare our results.

By far the most surprising result from our refinement of planetary radii, is the refinements of two planetary candidates orbiting the star TIC 201256771. Currently, 201256771 hosts two CTOIs, 201256771.01 and 201256771.02, which are recorded on ExOFOP-TESS as having radii of 24.72 $R_\oplus$ and 26.51 $R_\oplus$, respectively. With our revised radii, these candidate events observed in TESS Sector 1 now have radii comparable with stellar radii (Chen & Kipping 2017) of 96.17±5.34 $R_\oplus$ and 103.15±5.69 $R_\oplus$, respectively. This casts serious doubts about the planetary nature of these candidate events, especially with their orbital periods being only separated by 17 minutes, with the orbital periods of CTOI-201256771.01 and CTOI-201256771.02’s being stated as 3.75486 and 3.766667 days, respectively. Upon further investigation, this is a known eclipsing binary that has an orbital period nearly equal to the candidates, being 3.76170 days (Christiansen et al. 2008). From this data alone, we conclude that CTOI 201256771.01 and CTOI 201256771.02 are candidates of the same event, being the transit of the eclipsing companion to UNSW-V 320. Apart from this extreme example, the rest of our planetary radii fall nicely within the current literature values and their uncertainties, all of which can be found in Table 4. Upon the revision of this CTOI system, we re-checked the sensibility of the other CTOI systems within our planet-host sample. The orbital periods of CTOI 220402290.01 and CTOI 220402290.02 are 0.7833 and 0.7222 days respectively, or roughly 90 minutes. This would mean that their orbital separation would be comparable to their radii, which deems this system as extremely unstable. These transit events are likely caused by a single candidate, rather than two. Similarly, the orbital periods of CTOI 300903537.01 and CTOI 300903537.02 only differ by 36 minutes and are likely caused by the same candidate.

Of our known confirmed and candidate exoplanets, only three have measured mass values. The most conventional way that an exoplanet’s mass is determined is through the radial velocity technique. Specifically, an exoplanet’s line-of-sight mass, $M_p sin i$ is determined through measurement of the semi-amplitude of the host’s radial velocities measurement, $K_R$, orbital eccentricity, $e$, period $P$, and stellar mass $M_\odot$ (Lovis & Fischer 2010). If the orbital inclination, $i$, of the system is known, traditionally found through fitting models to the photometric transit curve, we can then calculate the planet’s true mass, $M_p$.

We use literature values for these planetary systems, namely WASP-182 b values from Nielsen et al. (2019a) as well as WASP-61 b and HD 103197 b values from Stassun et al. (2017). We combine these with the masses of their host stars in order to revise the planetary mass of the exoplanets. Our revised planetary mass values, along with the previous literature values, can be found in Table 5. As with the refined radii results, there is excellent overall agreement with our mass values compared to the literature. All three refined planetary mass values fall within 1-sigma error bars of the previous literature values. The biggest increase of planetary mass precision with our results comes from the Jovian type exoplanet HD 103197 b. We have refined the mass of HD 103197 b from a percentage error of 31% down to 2%, thanks largely due to the refinement in the stellar mass of HD 103197.

Overall, our refined planetary mass and radius results are in good agreement with their literature values. This also validates the overall good agreement with our refined stellar mass and radius values. Even though the change in planetary mass or radius of 10-20% might intuitively be insignificant in re-characterising Jovian worlds, it does however have larger implications for smaller planets like our own.

For example if an Earth-like planet in mass and radius (1.0 $R_\oplus$,1.0 $M_\oplus$), characterised by the TIC, was discovered orbiting around any of our GALAH-TESS stars, would this planet still be “Earth-like” with our revised stellar parameters? Using a similar approach to that of Johns et al. (2018), we can refine the planetary radius and mass of this fictitious Earth using both GALAH-TESS and TIC catalog values of stellar and planetary mass and radius values.
Figure 10. Simulation for the effects of parameter refinement on the mass and radius for a fictitious Earth-like planet discovered using the TIC catalog. The mass-radius relationships used for the dashed lines to show density curves for a 50% water-50% rocky, pure rocky (containing pure post-perovskite MgSiO$_3$), “Earth-like” (33% Fe and 67% rock) and pure iron worlds are from (Zeng et al. 2016). The black symbol “⊕” represents the Earth’s mass and radius. In extreme cases, a putative “Earth-like” planet varies between a scaled-up Enceladus-like world (i.e. dominated by layers of water and a silicate core), to a Fe-enriched, Mercury-like planet. This simulation shows the need for consistency and precision in exoplanetary mass and radius determination for meaningful comparative planetology.

Table 4. Our refined planetary radii values for confirmed and TESS candidate exoplanets. All literature radius values and transit depth values come from ExOFOP-TESS except for WASP-182 b, where its literature planetary radius and transit depth values are from Nielsen et al. (2019a). We have flagged problematic planetary candidates in bold. From our revised planetary radii, CTOI 201256771.01 and CTOI 201256771.02 now have radii comparable to the Sun, and thus are not exoplanets. The orbital periods of CTOI 220402290.01, CTOI 220402290.02, CTOI 300903537.01 and CTOI 300903537.02 are problematic and are likely duplications of the same event. This is discussed further in Section 4.1. Since some of these planet candidates are comparable in scale to that of Jupiter, the conversion between Jupiter’s radius to Earth’s is $R_J = 11.209 \, R_⊕$.  

| TOI/CTOI ID | TIC ID | ΔF [mmag] | Our $R_P$ [R$_⊕$] | Literature $R_P$ [R$_⊕$] |
|-------------|--------|------------|--------------------|------------------------|
| 439.01      | 13021029 | 9.04283 ± 0.00143 | 13.68 ± 0.20 | 13.27 ± 0.47 |
| 754.01      | 72985822 | 8.93564 ± 0.50239 | 12.00 ± 0.48 | 13.90 ± 13.91 |
| 815.01      | 102840239 | 1.25 ± 0.00155 | 2.81 ± 0.03 | 2.87 ± 0.13 |
| 201256771.01 | 201256771 | 84.34287 ± 8.98023 | 96.17 ± 5.34 | 24.72 |
| 201256771.02 | 201256771 | 97.59384 ± 10.39110 | 103.15 ± 5.69 | 26.51 |
| 220402290.01 | 220402290 | 21.84594 ± 2.32600 | 17.02 ± 0.93 | 17.15 |
| 220402290.02 | 220402290 | 44.09427 ± 4.69485 | 24.05 ± 1.30 | 24.25 |
| 300903537.01 | 300903537 | 94.16304 ± 10.02582 | 25.06 ± 1.33 | 25.10 |
| 300903537.02 | 300903537 | 11.02043 ± 1.17338 | 8.74 ± 0.48 | 8.75 |
| 300903537.03 | 300903537 | 3.74782 ± 0.39904 | 5.10 ± 0.28 | 5.11 |
| 1031.01     | 304021498 | 1.18 ± 0.00172 | 6.80 ± 0.08 | 6.91 ± 0.46 |
| 777.01      | 314305570 | 2.80673 ± 0.08351 | 8.56 ± 0.16 | 7.32 ± 1.15 |
| WASP-182 b  | 369455629 | 0.01067 ± 0.00000 | 8.90 ± 0.15 | 9.53 ± 0.34 |
| 1126.01     | 405862830 | 1.06 ± 0.00144 | 2.53 ± 0.02 | 2.62 ± 0.11 |
85% of our planets fall within ± Earth-like exoplanets are displayed in Figure 10. Roughly element, crucial in forming rocky material for planetary composition is described in Section 4.2. The degeneracy using stellar abundance ratios to infer an allowed, especially if the models used have three or more layers. This is typical for most that assume a three-layered planet (core, mantle, ocean) or a four-layered planet (core, mantle, ocean, atmosphere). Current Bayesian inference Dorn et al. (2015) and forward models Unterborn et al. (2018a,b) break down this degeneracy using stellar abundance ratios to infer an exoplanet's composition. These abundance ratios and their importance are described in Section 4.2. Our refined radius and mass values for these fictitious Earth-like exoplanets are displayed in Figure 10. Roughly 85% of our planets fall within ±10% of Earth-like mass and radius values. Beyond this ±10%, there is a wide variety of mass and radius values throughout the plot, which would suggest that these exoplanets that were once thought to be Earth-like, are now anything but. From Figure 10, there are varying degrees of bulk composition for these “Earth-like” worlds. In extreme cases, a putative “Earth-like” planet’s bulk density varies between a scaled-up Enceladus-like world (i.e. dominated by layers of water and a silicate core) (Zolotov et al. 2011; Schubert et al. 2007), to a possible remnant Jovian-world core dominated by iron (Mocquet et al. 2014; Benz et al. 2007) with the habitability of such worlds still up for debate (Lingam & Loeb 2019; Kite & Ford 2018; Noack et al. 2017). This shows that not only do we need better precision for stellar masses and radii, which better constrain the planetary mass and radius values, but there also needs to be a level of consistency across these fundamental parameters for future follow-up characterisation. There are already a wide variety of planetesimal and composition values for known super-Earth and Earth sized worlds, and thus there will be a wide variety of planetary compositions. A fundamental problem with inferring planetary compositions through mass-radius or terrestrial/quaternary diagrams (Brugger et al. 2017; Rogers & Seager 2010) is that they cannot uniquely predict the interior composition of a given exoplanet. A variety of different interior compositions can lead to identical mass and radius values (Unterborn & Panero 2019; Suissa et al. 2018; Unterborn et al. 2016; Dorn et al. 2015). This gives rise to an inherent density degeneracy problem. A wide variety of planetary compositions are allowed, especially if the models used have three or more layers. This is typical for most that assume a three-layered planet (core, mantle, ocean, atmosphere). Current Bayesian inference Dorn et al. (2015) and forward models Unterborn et al. (2018a,b) break down this degeneracy using stellar abundance ratios to infer an exoplanet’s composition. These abundance ratios and their importance are described in Section 4.2. 4.2 Importance of Stellar Abundances to Exoplanetary Science Within our own Solar system, observations show that the relative abundances of refractory elements such as Fe, Mg and Si, elements crucial in forming rocky material for planets like ours to build upon, are similar within the Sun, Earth, the Moon and Mars (Wang et al. 2019b; Lodders 2003; McDonough & Sun 1995; Waln & Drebues 1994). The bulk planetary and stellar ratios of these elements during planetary formation are also similar, suggesting that stellar Fe/Mg and Mg/Si can assist with determining the building blocks of the planets they host (Thiabaud et al. 2015, 2014a; Bond et al. 2010b). These elemental abundances can help us understand what elements favour certain planetary architectures and can also provide constraints on the internal geological composition of exoplanets (Unterborn et al. 2018a; Brugger et al. 2017; Dorn et al. 2017a, 2015). In particular, the elemental abundance ratios of Mg/Si, Fe/Mg and C/O are fundamental for probing the mineralogy and structure of rocky exoplanets. The formation, structure and composition of exoplanets is extremely complex, with these generalisations not taking into account planetary migration or secondary processes such as giant impacts. A more comprehensive analysis of GALAH DR2’s abundances trends and implications for planet-building elements can be found in Bitsch & Battistini (2020). 4.2.1 Estimating the size of a Rocky Planet’s Core Through Stellar Fe/Si Ratios The amount of mass contained within a rocky exoplanet’s core is determined by its Fe/Si ratio (Dorn et al. 2015; Unterborn et al. 2018a; Brugger et al. 2017). An increasing Fe/Si ratio would result in a larger core mass fraction compared to a larger mantle core fraction for smaller values of Fe/Si. Within our Solar system, Earth (McDonough & Sun (1995) and Mars (Waln & Drebues 1994) have comparable bulk Fe/Si values to that of photospheric Solar values (Lodders et al. 2000; Lodders 2003). Mercury, however, is an anomaly with its bulk Fe/Si value estimates ranging from ~5-10, corresponding to a core mass fraction of ~45-75% compared to a Fe/Si ratio near ~1.00 and a core mass fraction of 32% for Earth (Nittler et al. 2017; Brugger et al. 2018; Wang et al. 2019b). It is possible for the majority of iron to be contained within silicate material including bridgmanite (MgSiO₃/Fe₂SiO₃), magnesiowüstite (MgO/FeO), olivine (Mg₂SiO₄/Fe₂SiO₄) and pyroxenes (Mg₂Si₂O₆/Fe₂Si₂O₆) for bulk Fe/Si values less than 1.13 (Alibert 2014). For Fe/Si > 1.13, models suggest that an iron core needs to be present within a rocky exoplanet to explain such a high ratio. This limit is calculated by simple stoichiometry and may not reflect the actual distribution of iron throughout a rocky exoplanet’s core and mantle. The oxygen fugacity can also af-
fect the distribution of a planet’s iron distribution (Bitsch & Battistini 2020), oxidising with mantle constituents instead of being differentiated into a core if the oxygen fugacity is too high (Elkins-Tanton & Seager 2008). This would result in a lower core mass fraction compared to situations of lower fugacity. Current models show that iron can be taken up in the mantle (Dorn et al. 2015; Unterborn et al. 2018a) as well as silicon being taken up within an iron core (Hirose et al. 2013). Thus, Fe/Mg is a better proxy for core-to-mantle ratio and is produced within the GALAH-TESS catalog.

Figure 11 shows the distribution of Fe, Mg and Si for our sample of GALAH-TESS stars. We can calculate the core mass fraction of potential rocky planets hosted by GALAH-TESS stars using stoichiometry by the equation:

\[
\#Fe \times \mu_{Fe} / (\#Mg \times (\mu_{Mg} + \mu_O) + \#Si \times (\mu_{Si} + 2 \times \mu_O) + \#Fe \times \mu_{Fe})
\]

(3)

where \#X represents the molar abundance of element X and \(\mu_X\) is the molar weight of that element. We are able to use this estimation as Fe, Mg and Si all have similar condensation temperature (Lodders et al. 2009) and thus thermal processes are unlikely to fractionate the elements relative to each other. That is while a planet may have significantly fewer atoms of Fe and Mg than the host star, the Fe/Mg ratio of the star and planet may only be different by \(\sim 10\%\) (Bond et al. 2010a; Thiabaud et al. 2014b; Unterborn & Panero 2017). While mantle stripping by large impacts may increase the planet’s Fe/Mg ratio (e.g., Bonomo et al. 2019). Equation 3 represents a reasonable upper-bound for CMF for most systems. As mentioned above, changes in oxygen fugacity will convert some core Fe into mantle FeO, which will lower the CMF for a given bulk composition. From this ternary we can see that stellar abundances outline a wide range of CMF compared to the Earth and Sun, with their abundances falling near the middle of the distribution (Figure 12). Less than 0.3 % of our stars have Fe/Si > 1.13 (Figure 12), therefore the rocky planets possibly orbiting GALAH-TESS stars may have their iron content distributed between both core and mantle layers with marginally lower CMF than predicted in Figure 11.

4.2.2 Mantle Compositions of Rocky Exoplanets Through Stellar Host Mg/Si and C/O Ratios

The structure and composition of super-Earths and sub-Neptunes can be constrained through theoretical models using their host’s Mg/Si and C/O elemental ratios. The stellar C/O abundance chemically controls the silicon distribution amongst oxides and carbides (Bond et al. 2010b; Carter-Bond et al. 2012; Duffy et al. 2015). For those stars with C/O values less than 0.8, Mg/Si controls the mantle chemistry by varying the relative proportions of olivine, pyroxenes and oxides. However, within this realm of low C/O values, there are two distinct regimes in which the Mg and Si are distributed within the mantle:

- In a “silicon-rich” environment, whereby the Mg/Si < 1, the upper mantle will be dominated by ortho- and clino-
pyroxene, majoritic garnet (Mg3(Si4O10)2) as well as SiO_2 (either as quartz or coesite) with the lower mantle consisting of bridgmanite ((Mg,Fe)SiO_3) and stishovite (SiO_2). As Mg/Si decreases, the proportion of stishovite will increase at the cost of bridgmanite in the lower mantle.

- For larger values of Mg/Si, where Mg/Si > 1, a rocky planet’s upper mantle will mostly comprise of olivine (Mg2SiO_4), pyroxenes and majoritic garnet, with bridg-
manite and magnesioferritite (or ferropericlase) ((Mg,Fe)O) in lower mantle. As the Mg/Si ratio increases, so does the amount of olivine and ferropericlase within the rocky planet’s upper and lower mantle respectively. This regime of planetary composition is akin to rocky worlds (i.e Mars and Earth) within our Solar system and thus labelled as “terrestrial-like” mantle compositions within our paper. (Unterborn & Panero 2017; Duffy et al. 2015; Carter-Bond et al. 2012; Bond et al. 2010b). As Mg/Si increases, the proportion of magnesioferritite will increase at the cost of bridgmanite in the lower mantle.

However these compositions only extend for C/O < 0.8. For C/O > 0.8, exotic mantle compositions of graphite and the carbides including SiC can start to dominate the geo-
chemical composition of an exoplanet’s core and mantle, when planets form within a protoplanetary disk’s innermost re-
gion (Carter-Bond et al. 2012; Miozzi et al. 2018; Kuchner & Seager 2005; Wilson & Militzer 2014; Nisr et al. 2017; Unterborn et al. 2014). These “carbon-rich” worlds can extend out through carbon-rich disks and can even form with C/O ratios as low as 0.67 (Moriarty et al. 2014). However, the habitability of such worlds is still under debate, with some studies suggesting that habitability is unlikely. This is because theoretical models suggest that these worlds would likely be geodynamically inactive planets and would limit the amount of carbon-dioxide degassing into its atmosphere (Unterborn et al. 2014).

Our C/O and Mg/Si distribution for the GALAH-TESS stars are found in Figure 13. Of our 47,000+ sample, only 8832 stars have C/O and Mg/Si ratios as most stars’ C or O abundances were flagged by The Cannon. This sample also includes exoplanet host WASP-61 and candidate hosts UCAC4 238-000232 (TOI-754) and HD81655 (TOI-1031). A total of 36.6% of these stars have C/O < 0.8 and Mg/Si > 1 values, suggesting that these stars may potentially host exoplanets that would have compositions akin to planets found within our own Solar system, including both known exoplanet-hosting stars WASP-61 and TOI-754. Both WASP-61 and TOI-754 however are only known to host Jupiter-sized worlds that would have significantly dif-
ferent core structures to that of smaller super-Earth and sub-Neptune exoplanets (MacLeod et al. 2014; Fordney & Nettelmann 2010; Buhlkr et al. 2016). However, future studies may discover smaller worlds around these stars. Within our GALAH-TESS sample, 46.4 % of stars have Mg/Si and C/O ratios suggesting that these stars could possibly host rocky planets that are “silicon-rich” compared to planets found within our Solar System. The candidate exoplanet host TOI-1031 is such a system that could boast Silicon-rich worlds with a Mg/Si value of 0.91 ± 0.20.

Distributions of Mg/Si similar to the ones we find within our sample have also been discovered with other surveys: ~60% of the Brewer & Fischer (2016) sample of FGK dwarfs in the local neighbourhood also falls between 1 < Mg/Si . Photospheric measurements of planet-hosting stars show a range of Mg/Si values ranging from 0.7 to 1.4 (Delgado Mena
Figure 11. Ternary diagram of the Fe, Mg and Si abundances from the for our GALAH-TESS stars assuming a Solar abundance model of Lodders et al. (2009). In general, the closer to an individual corner of the ternary a data point falls the greater the proportion of that element in the resulting planet assuming stellar composition roughly reflects planetary composition (Bond et al. 2010a; Thiabaud et al. 2014b; Unterborn & Panero 2017). Individual points are color-coded to show the maximum core mass fraction (CMF) of the planet assuming all Fe is present in the core and Mg and Si are in their oxide forms (MgO, SiO$_2$). CMF is therefore calculated by

$$\text{CMF} = \frac{\#Fe \times \mu_{Fe}}{\#Mg \times (\mu_{Mg} + \mu_O) + \#Si \times (\mu_{Si} + 2 \times \mu_O) + \#Fe \times \mu_{Fe}}$$

where $\#X$ represents the molar abundance of element $X$ and $\mu_X$ is the molar weight of that element. The Earth (McDonough 2003) and Solar (Lodders et al. 2009) abundances are shown for reference.

Surprisingly, less than 1 % of GALAH-TESS stars have a C/O ratio greater than 0.8, suggesting that these stars may host “Carbon-Rich” worlds, that will have geological structures unlike any object within our Solar system. Our median C/O value is 0.44 ± 0.13 which is somewhat comparable to other stellar surveys (Brewer & Fischer 2016; Pettigura & Marcy 2011; Delgado Mena et al. 2010) and population statistics (Fortney 2012) – but could be an overestimate from galactic chemical evolution models (Fortney 2012). The discrepancies between these surveys are likely due to different stellar populations, methodologies used to derive stellar abundances or Solar normalisations used as discussed in Section 3.2.

We should note that GALAH’s [O/H] abundances do account for non-LTE effects but are only taken from at most four lines, with non-LTE effects for [O/H] abundance taken for the O$\text{I}$ triplet near $\sim$777.5 nm (Buder et al. 2018; Gao et al. 2010; Brewer & Fischer 2016), while our planet host and candidate stars Mg/Si values range from 0.9 to 1.1. Our median Mg/Si value is 0.98 ± 0.22 which is lower than Brewer & Fischer (2016)’s Mg/Si median value of 1.02. The larger spread of Mg/Si values in other surveys might be due to different Solar normalisations but seems more likely that this is due to a different stellar sample and methodologies to derive chemical abundances. (Hinkel et al. 2014) showed that even for iron, the spread in for the same stars gathered from various groups was 0.16 dex. Thus, more work is needed to better understand the underlying systematics and variations of stellar abundances from various surveys and research groups.
et al. 2018; Amarsi et al. 2016a). This triplet is known to over-estimate abundances if non-LTE effects are not taken into account (Teske et al. 2013). Brewer & Fischer (2016)’s approach considers molecular OH lines and numerous more carbon lines, such that our results might be overestimated with respect to theirs. Teske et al. (2014) found that there is currently no significant trend between planet-hosts, in particular the occurrence of hot-Jupiters, and their C/O values.

4.2.3 How are Stellar Abundances Linked to Planetary Formation?

There is theoretical evidence suggesting that the abundance ratios of refractory materials stay relatively constant throughout a protoplanetary disk, but it is misleading to suggest that volatile abundance ratios will be constant through the disk. Elemental abundance ratios can change through a protoplanetary disk depending upon the concentration of material and temperature profile of the disk (Bond et al. 2010b; Carter-Bond et al. 2012; Unterborn & Panero 2017). There are studies that suggest that estimates of the devolatilisation process within a protoplanetary disk could aid in determining the bulk elemental abundances of rocky worlds, assuming they have formed where they are currently situated within their own planetary system (Wang et al. 2019b).

If we want to determine if a world has bulk composition as the earth, studies suggest that the errors with the elemental abundances themselves need to be further refined with uncertainties better than ~ 0.04 dex needed for such a comparison (Hinkel & Unterborn 2018; Wang et al. 2019b). Even further, if we want to differentiate between unique planetary structures within a rocky exoplanet population, the uncertainties for Fe, Si, Al, Mg and Ca abundances need to be less than 0.02, 0.01, 0.002, 0.001 and 0.001 dex respectively (Hinkel & Unterborn 2018). These uncertainties, especially for Al, Mg and Ca are unobtainable with current detection methods and Solar abundance normalisations. Hence, if we do want to accurately determine an exoplanet’s interior and composition, which has vast implications for its habitability, then precision on spectroscopic abundances and Solar normalisations themselves also have to significantly increased.

The relationship between elemental abundances and planetary architectures is a complex one. There is an overall trend that hot-Jupiter systems favour iron-rich hosts (Fischer & Valenti 2005; Mortier et al. 2013) and early evidence that super-Earths are predominantly found around metal-poor and α–rich stars (Adibekyan et al. 2012) and new work with machine-learning algorithms suggest elemental indicators for hot-Jupiter hosting stars apart from Fe are O, C, and Na (Hinkel et al. 2019). Work by Adibekyan et al. (2016); Sousa et al. (2019) shows super-Earths orbiting metal-rich stars have orbits that extended beyond their metal-poor hosted peers but contradicts Petigura et al. (2018) who indicate that short-period super-Earths orbit metal-rich stars. Sousa et al. (2019) also suggest the mass of planets increases with the host star metallicity, but contradicts Teske et al. (2019), which did not find such a correlation. Brewer et al. (2018) found that compact-multi systems are more common around metal-poor stars, showing a large [Fe/H] vs Si/Fe parameter space unfilled by single hot-Jupiters but filled with compact-multi systems for planet hosts with [Fe/H] values below 0.2 and Si/Fe values higher than 1.4. We have created a similar figure for our small exoplanetary sample, to somewhat forward predict the types of planetary architectures our GALAH-TESS stars might host. Figure 14 shows that the majority of planet hosts and candidates fill quadrant B of this phase-space, where Brewer et al. (2018) found a diverse range of planetary architectures occupying this space. All of our confirmed and candidate systems favour iron-rich, silicon-poor stars, where a diverse range of exoplanetary architectures are likely to be found. This matches our current, though very small sample with single-planet systems hosting sub-Neptune to Jovian like worlds.

5 CONCLUSION

The aim of this paper is to aid TESS follow-up teams with a catalog of high precision physical and chemical stellar parameters for stars being observed with the space-based exoplanet survey satellite. We have cross-matched GALAH DR2 with the TIC to provide the physical and chemical characteristics for over ~47,000 stars, eleven of which confirmed planet-hosts or planetary candidates discovered by the TESS mission. The refinement of stellar radii and masses of those planet-hosting stars have improved the mass and radius measurements of the confirmed and candidate exoplanets they host, with a median relative uncertainty for our planetary mass and radius values being 5% and 4%, respectively. From these refinements, we have increased the planetary radii of CTOI-201256771.01 and CTOI-201256771.02 to near Solar values of 96.17 R_⊙ and 103.15 R_⊙, and with further investigation, have indicated that these transit events were likely caused by the eclipsing binary companion of UNSW-V 320 A. We also cast serious doubts over the candidate events CTOI-220402290.01, CTOI-220402290.02, CTOI-300903537.01 and CTOI 300903537.02 as their orbital periods alone suggest that these candidate systems are likely coming from one source and not two. Our updated mass

Figure 12. Of the 47,285 stars within our sample, only 134 have Fe/Si values greater than 1.13 which would indicate the vast majority of our possible rocky worlds will have their iron content distributed between their iron and mantle layers. An iron-core must be present beyond Fe/Si values of 1.13 to explain such a high Fe/Si ratio. The white star within the histogram depicts the Sun’s photospheric Fe/Si value of 0.85 (Lodders et al. 2009).
Figure 13. Distribution of all stars that have both measured C/O and Mg/Si ratios. These ratios can help inform astronomers on the likely composition of probable rocky worlds these stars may host. A total of 53.6 % of these stars have C/O < 0.8 and Mg/Si > 1 values that would suggest that these stars may potentially host planets that would be similar in geological composition to Earth and Mars. These potential rocky worlds would host olivine and pyroxene within their upper mantle and bridgmanite and magnesiowüstite (or ferropericlase) in their lower mantle. That leaves 46.4 % of stars that will host planets unlike any worlds within our Solar system. These include 45.4 % of stars potentially hosting “Silicon-Rich” rocky worlds with stellar abundance ratios C/O < 0.8 and Mg/Si < 1, indicating that these worlds could contain pyroxene + SiO within both their upper and lower mantles. Only 1 % of GALAH-TESS stars have C/O > 0.8 indicating that they might host rocky worlds with carbon-rich mantles. Planet-hosting (cross) and candidate stars (TOI (upright triangle)) measured Mg/Si and C/O values are displayed on the figure with the Sun’s Mg/Si and C/O values depicted with a white star (Lodders et al. 2009).

Our catalog contains the elemental abundances for 23 elements which have been normalised by (Lodders et al. 2009) to not only drive consistency within the community, but to also make it easier for comparisons of elemental abundances from other abundance driven, stellar surveys to ours. The GALAH-TESS catalog includes the elemental abundance ratios for C/O, Mg/Si, Fe/Mg and Fe/Si which can help astronomers and planetary scientists make predictions about the composition and structure of potential rocky worlds orbiting these stars. Our stellar C/O and Mg/Si distributions suggest that the majority of GALAH-TESS stars will likely host worlds similar in composition to that of Earth and Mars, with over 54 % of stars hosting Mg/Si > 1, and C/O < 0.8. However, 46 % of stars have atmospheric abundance ratios of either Mg/Si < 1 and C/O < 0.8 or C/O > 0.8, suggesting that these stars may host rocky worlds with geological compositions unlike any planet found within our Solar system. These values will change dependent upon the Solar normalisation used, hence the need for a standard Solar normalisation within the exoplanetary community. It is important in our language that a truly Earth-like planet has yet to be discovered (Tasker et al. 2017), but with our catalog and TESS’s extended mission planned for the Southern Hemisphere in 2021, we can move closer to answering humankind’s grandest question — are we truly alone?

SOFTWARE

AstroPy (Astropy Collaboration et al. 2013), Astroquery (Ginsburg et al. 2019), Isochrones (Morton 2015), Matplotlib (Hunter 2007), MultiNest (Feroz et al. 2019, 2009; Feroz & Hobson 2008), Multiprocessing (McKerns et al. 2020).
Figure 14. In Brewer et al. (2018), the authors discovered that compact multi-planet systems favoured iron-poor, silicon rich stars with a higher population of multiplanetary systems favouring the A quadrant in this Figure. A wider range of planetary systems, including single-systems consisting of hot-Jupiters were more common within quadrant B of this Figure. This figure shows our [Fe/H] and Si/Fe abundance ratios for 43162 GALAH-TESS stars. Based upon our results, a more diverse range of planetary systems will be uncovered around GALAH-TESS stars, with the majority of our stars lying in quadrant B. The white star represents the Sun’s [Fe/H] and Si/Fe values with known confirmed or candidate hot-Jupiter (cross) and other (triangle) planetary systems shown for comparison.

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This research has made use of the Exoplanet Follow-up Observation Program website, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program.

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**DATA AVAILABILITY**

The data underlying this article are available in the article and in its online supplementary material.

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**GALAH-TESS Catalog**
This paper has been typeset from a TeX/LaTeX file prepared by the author.
| Name | Units | Data type | Description |
|------|-------|-----------|-------------|
| TICID | int64 | TESS Input Catalog (TIC) Identifier |
| TWOMASS | int64 | Two Micron All-Sky Survey (2MASS) Identifier |
| GALADR2 | long64 | GAIA DR2 Identifier |
| PRIORITY | float64 | TIC v8 priority |
| RA | deg | float64 | J2000 right ascension from 2MASS |
| DEC | deg | float64 | J2000 declination from 2MASS |
| TEFF | K | int64 | GALAH DR2 Effective temperature |
| E_TEFF | K | int64 | Uncertainty in TEFF |
| LOGG | dex | float64 | GALAH DR2 Surface gravity |
| E_LOGG | dex | float64 | Uncertainty in LOGG |
| MH | dex | float64 | GALAH DR2 overall metallicity |
| E_MH | dex | float64 | Uncertainty in MH |
| ALPHAFE | dex | float64 | [$\alpha$/Fe] abundance |
| E_ALPHAFE | dex | float64 | Uncertainty in ALPHAFE |
| VMAG | mag | float64 | V magnitude from TIC |
| E_VMAG | mag | float64 | Uncertainty in VMAG |
| TMAG | mag | float64 | TESS magnitude from TIC |
| E_TMAG | mag | float64 | Uncertainty in TMAG |
| HMAG | mag | float64 | 2MASS H magnitude from TIC |
| E_HMAG | mag | float64 | Uncertainty in HMAG |
| JMag | mag | float64 | 2MASS J magnitude from TIC |
| E_JMag | mag | float64 | Uncertainty in JMag |
| KMAG | mag | float64 | 2MASS K magnitude from TIC |
| E_KMAG | mag | float64 | Uncertainty in KMAG |
| GMAG | mag | float64 | GAIA G magnitude from TIC |
| E_GMAG | mag | float64 | Uncertainty in GMAG |
| GRPMAG | mag | float64 | GAIA G_RP magnitude from TIC |
| E_GRPmag | mag | float64 | Uncertainty in GRPMAG |
| GBPMAG | mag | float64 | GAIA G_BP magnitude from TIC |
| E_GBPmag | mag | float64 | Uncertainty in GBPMAG |
| PLX | mas | float64 | Parallax from TIC |
| E_PLX | mas | float64 | Uncertainty in PLX |
| DIST | pc | float64 | Distance from TIC |
| E_DIST | pc | float64 | Uncertainty in DIST |
| RADIUS | R⊙ | float64 | isochrone Stellar radius |
| E_RADIUS | R⊙ | float64 | Uncertainty in RADIUS |
| MASS | $M_\odot$ | float64 | isochrone Stellar mass |
| E_MASS | $M_\odot$ | float64 | Uncertainty in MASS |
| RHO | gcm⁻³ | float64 | isochrone Stellar density |
| E_RHO | gcm⁻³ | float64 | Uncertainty in RHO |
| LUM | L⊙ | float64 | Stellar luminosity |
| E_LUM | L⊙ | float64 | Uncertainty in LUM |
| AGE | Gyr | float64 | isochrone Stellar age |
| E_AGE | Gyr | float64 | Uncertainty in AGE |
| EEP | int64 | MIST isochrone equivalent evolutionary phase |
| E_EEP | int64 | Uncertainty in EEP |
| RV | kms⁻¹ | float64 | GALAH DR2 Radial velocity from internal cross-correlation against data |
| E_RV | kms⁻¹ | float64 | Uncertainty in RV |
| VSNI | kms⁻¹ | float64 | GALAH DR2 Line of sight rotational velocity |
| E_VSNI | kms⁻¹ | float64 | Uncertainty in VSNI |
| VMIC | kms⁻¹ | float64 | GALAH DR2 Microturbulence velocity |
| E_VMIC | kms⁻¹ | float64 | Uncertainty in VMIC |
| RVXVEN | AU | float64 | Recent Venus Habitable Zone |
| RVRUNGN | AU | float64 | Runaway Greenhouse Habitable Zone |
| RVMOGN | AU | float64 | Moist Greenhouse Habitable Zone |
| RVMAXGN | AU | float64 | Maximum Greenhouse Habitable Zone |
| RVEARMAR | AU | float64 | Early Mars Habitable Zone |
| XH | dex | float64 | [X/H] abundance for element X |
| EXH | dex | float64 | [X/H] Uncertainty in XH |
| CO | (C/O) | float64 | abundance ratio |
| E_CO | (C/O) | float64 | Uncertainty in CO |
| MGSI | float64 | (Mg/Si) abundance ratio |
| E_MG_SI | float64 | Uncertainty in MG_SI |
| FE_MG | float64 | (Fe/Mg) abundance ratio |
| E_FE_MG | float64 | Uncertainty in FE_MG |
| FE_SI | float64 | (Fe/Si) abundance ratio |
| E_FE_SI | float64 | Uncertainty in FE_SI |