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High-Resolution Abundance Analysis of Stars with Small Planets Discovered by Kepler

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ABSTRACT

Using high-resolution, high signal-to-noise ratio Keck/HIRES spectra we have derived the parameters and abundances of 17 elements of four planetary host stars discovered by Kepler: Kepler-97, Kepler-128, Kepler-131, and Kepler-411. All four stars are known to host small planets (from 0.8 to 1.8 Earth radii), and densities have been determined for planets in two of the systems. We find the metallicities of the stars to range from [Fe/H] $= -0.17$ to [Fe/H] $= +0.13$ (on a scale where the Sun has a metallicity of [Fe/H] $= 0.00$). This suggests that small planet formation occurs over a wide range of metallicities, in contrast to large, Jupiter-size planets which have been shown to form preferentially in high-metallicity environments. In addition, our four stars are found to have elemental abundances which fall along trends defined by a large sample of stars within the disk of the Galaxy. Based on this result, small planets appear to form around stars that have compositions typical of the general Galactic population. The detailed compositions of these host stars, along with densities of small planets, will provide important constraints for models of small planet formation.

1 INTRODUCTION

Since the discovery of the first exoplanet planet orbiting a solar-type star (Mayor & Queloz, 1995), a small number of theories have been postulated about the conditions required for planetary formation. Gonzalez (1997, 1998) provided one of the first pieces of evidence with the discovery that the host stars of Jupiter-type, giant planets, in general, have much larger metallicities ([Fe/H])[1] than stars without known planets. Multiple groups have confirmed this result (e.g. Santos et al., 2001; Fischer & Valenti, 2005; Ghezzi et al., 2010b) along with substantial observational evidence that has indicated high metallicity is an intrinsic property of these planetary systems (e.g. Fischer & Valenti, 2005; Ghezzi et al., 2010b). Core-accretion models of planetary formation, which have gained wide acceptance within the astronomical community, state that a rocky planetary core is formed first by the coagulation of small dust particles and then by subsequent collisions of the growing rocky fragments. The build-up of a core can end in the formation of a smaller, terrestrial planet or can continue until the planetary core is massive enough to accrete vast quantities of gases, eventually leading to the formation a Jupiter-like, giant planet. Ida & Lin (2004) suggest that the growth of the planetary cores is more efficient in higher metallicity environments, and can thus account for the planet-metallicity correlation.

Gonzalez (1997) proposed an alternative explanation for the planet-metallicity correlation. He theorized that the metallicities of these host stars are not primordial, i.e., the result of the initial conditions of stellar formation, but rather due to the process of stellar pollution. He suggested that the processes occurring in the protoplanetary disk, such as planetary objects being pushed into the star by larger objects in a more distal orbit, would cause the accretion of metal-rich materials onto the star and thus raising the metallicity of the star. Furthermore, Gonzalez postulated that this enrichment from planetary accretion should leave behind a trend in the photospheric abundances that would correlate with the condensation temperatures (T_c) of the elements, i.e., high-T_c refractory elements would be more abundant than low-T_c volatile elements. Support for Gonzalez's theory is lacking, however, as modeling efforts have not conclusively determined if the accreted material would leave an observable imprint on a stellar photosphere (Pinsonneault et al., 2001; Murray & Chaboyer, 2002; Vauclair, 2004) and attempts to identify trends with T_c (Smith et al., 2001; Ecuvillon et al., 2006a; Gonzalez, 2006; Schuler et al., 2011) have not found significant differences between stars with and without known giant planets.

Buchhave et al. (2012) investigated the metallicities of the host stars of 226 small exoplanet candidates discovered by NASA's Kepler mission (Borucki et al., 2011) and found that, as previously evidenced, Jupiter-type, giant planets tend to form around host stars with higher metallicities. Notably, Buchhave et al. (2012) found that smaller, potentially terrestrial, planets are capable of forming around stars with a wide range of metallicities. Their result suggests that terrestrial planet formation may be widespread throughout the disk of the Galaxy, with no special requirements of high metallicity for their formation. The authors suggested that up to 25% of all stars in the Galactic Disk could host a terrestrial planet.

Melendez et al. (2009) further investigated the idea of T_c trends being a possible indicator of terrestrial planet formation by showing that the Sun is *deficient* in refractory elements relative to volatile elements when compared to 11 non-planet hosting solar twins, stars that have stellar parameters that are nearly identical to those of the Sun. The authors also show that there is a strong correlation between the abundances of these refractory elements and T_c, such that the abundances decrease with an increasing T_c. This observation is contrary to the original expectations of Gonzalez's theory. Melendez et al. (2009) interpret their finding as a potential signature of terrestrial planet formation in the solar system, postulating that the depletion of refractory elements in the solar photosphere is due to those elements being locked up in the four terrestrial planets—Mercury, Venus, Earth, and Mars. A comparison of solar refractory

[1] The [X/H] notation (X being any given element) is the ratio $[\mathrm{X/H}] = (\log N(X)_* - \log N(H)_*) - (\log N(X)_\odot - \log N(H)_\odot)$ where $\log N(H) = 12$. This is generally defined as a relative abundance, the ratio of an element's abundance in the star to the element's abundance in the Sun, where the sun is scaled such that $[\mathrm{X/H}]_\odot = 0$.

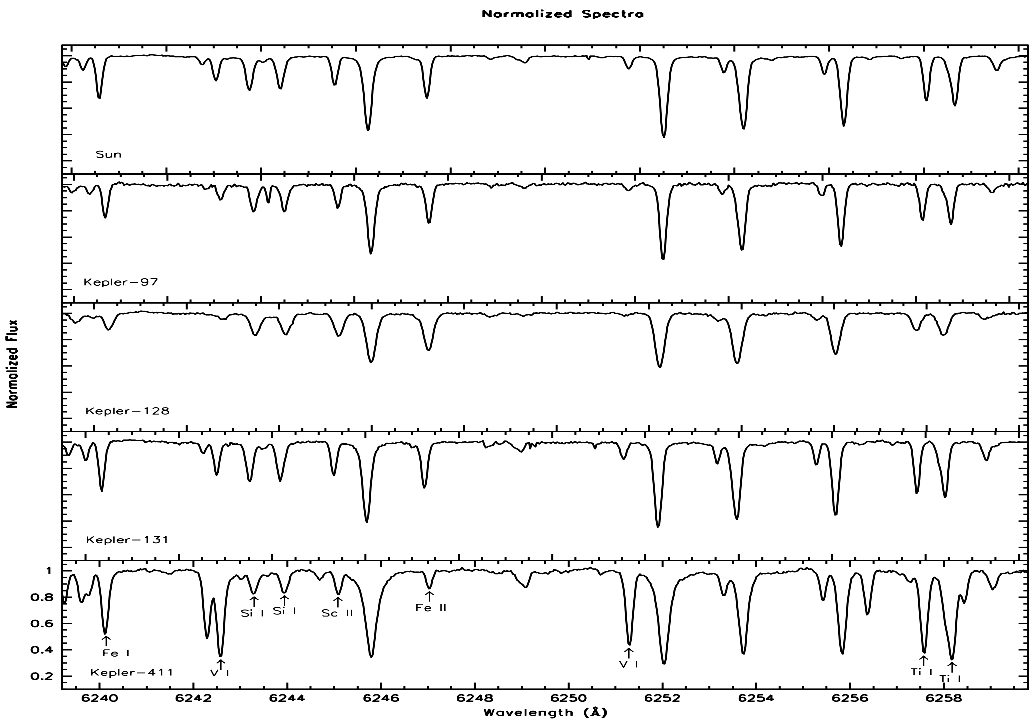

Fig. 1: High-resolution Keck spectra of four Kepler stars and the Sun. A selection of measured absorption lines are marked in the lower panel.

abundances to those of nearby solar twins and solar analogs (stars with stellar parameters similar to those of the Sun) found that about 85% of the stars do not show the proposed terrestrial planet signature (Ramirez et al., 2009, 2010). These studies then speculate that the remaining 15% of stars are potential terrestrial planet hosts.

The studies discussed above highlight the primary objective of performing chemical abundance studies on planetary host stars: identifying possible vestiges of planet formation that will bring a greater understanding of both the formation process and evolution of exoplanets. Here, we present the results of a high-precision abundance analysis of 16 elements for four Kepler host stars with known small planets to investigate a metallicity requirement for small planet formation and to also compare the chemical abundances of our sample against the Galactic stellar population.

2 METHODS

Observations

Observations of the four Kepler stars in our sample were carried out as part of the Kepler Follow-up Program—a dedicated effort orchestrated by Kepler science team members to confirm planetary candidates discovered by Kepler and to characterize the planetary systems and their host stars—using W.M. Keck Observatory's the 10-m Keck-I telescope and the High-Resolution Echelle Spectrograph (HIRES). The advantage of an echelle spectrograph over a more typical single-order spectrograph is that the echelle captures more of the light and provides a larger wavelength coverage at a very high resolution. Resolution is defined as $\lambda/\Delta\lambda$ where λ is the wavelength and $\Delta\lambda$ is the smallest distinguishable piece of a spectrum. Our spectra are characterized by a high resolution of $\lambda/\Delta\lambda = 60,000$, which permits us to measure, in detail, the absorption lines of numerous elements. Sample spectra are shown in Figure 1.

We retrieved the high quality spectra used in our study from the Kepler Community Follow-Up Program (CFOP) database. The process to identify stars to be analyzed included searching the Exoplanet Archive (http://exoplanetarchive.ipac.caltech.edu) for host stars that have small, terrestrial planets with measured densities, if possible. We then utilized the CFOP database search engine to pare down our list to include only stars with HIRES spectra that meet our strict data quality requirements (signal-to-noise ratio $\geq$ 150).

Abundance Analysis

We have derived the abundances of 16 elements for each star directly from equivalent width (EW) measurements of spectral absorption lines. The EW is a measurement of the strength of the absorption line which is directly related to the abundance of a given element in the star. The EWs were measured by fitting Gaussian profiles to the lines using the one-dimensional spectrum analysis package SPECTRE (Fitzpatrick & Sneden, 1987).

Abundances were then derived from the EW measurements using an updated version of the spectral analysis code MOOG (Sneden, 1973) and model atmospheres interpolated from Kurucz ATLAS9 grids constructed assuming the convective overshoot approximation. The model atmosphere is a quantitative representation of the conditions in the stellar photosphere and thus provides the framework in which the absorption lines are forming. The MOOG software combines our EW measurements with the model atmosphere to produce a derived abundance.

Stellar Parameters

Stellar parameters, T_{eff} (effective temperature; essentially the estimate of the surface temperature of a star), log g (the surface gravity related to the internal pressures of the star), ξ (microturbulent velocity; small-scale turbulence within the photosphere) and metallicity (the bulk elemental composition of the star) for each star have been derived using standard spectroscopic techniques. This is done by requiring excitation and ionization balance of abundances derived for neutral (Fe I) and singly ionized (Fe II) iron lines. The process begins by ensuring there is no statistically significant correlation between the EW of the measured Fe I lines and their excitation potentials (EP, χ), i.e., that the strength of the absorption feature is not directly related to the EP of the line. Unique parameter solutions are only guaranteed if no correlations exist. For two of the stars, a significant correlation was found which required the removal of a small number of Fe I lines in order to remove the correlation. The parameters are altered, and new stellar models are created until the derived iron abundances meet three conditions. First, the derived [Fe I/H] is equal to the derived [Fe II/H] (ionization balance). Second, there exists zero correlation between [Fe I/H] and lower EP for each line (excitation balance). Third, there is zero correlation between [Fe I/H] and reduced EW [log(EW/λ)].

The list of iron lines used here in our study is taken from Schuler et al. (2011) and were chosen for minimal potential blending, proximity to order edges, or any other defects that may prevent the accurate measurement of a line. This list resulted in 65 Fe I lines and 12 Fe II lines. We note that not all lines were measurable for each star in the sample due to relative data quality and random noise in the spectra. Atomic parameters (χ and transition probabilities) were obtained from the Vienna Atomic Line Database (VALD; Piskunov et al. (1995)). We calculated uncertainties in the stellar parameters by forcing 1σ (one standard deviation) correlations in the previously described relations. For T_{eff}, the uncertainty is the change in temperature required to produce a correlation coefficient in [Fe I/H] versus EP significant at the 1σ level. The same process was done for ξ by forcing a correlation between [Fe I/H] and EW. To determine the uncertainty in log g, an iterative process is required, as thoroughly described in Bubar & King (2010). In Table 1, the final parameters and their 1σ uncertainties are provided along with the mean [Fe I/H] and [Fe II/H] abundances and the uncertainty in the means.[2] . In addition to Fe, the abundances of 15 other elements were derived and the line list is the same as used by Schuler et al. (2011)

Abundance Uncertainties

Uncertainties in our derived abundances can arise due to errors in the adopted stellar parameters as well as in the measurement of individual lines of a given element. We first determine the abundance uncertainties due to stellar parameters by calculating how sensitive the elemental abundances are to a change in the adopted parameters. This was done for changes of ±150 K in T_{eff}, ±0.25 dex in log g, and $\pm0.30 \mathrm{kms}^{-1}$ in ξ. The abundance uncertainty due to each parameter is then calculated by scaling the sensitivity by the amount of uncertainty in each parameter. The final total uncertainties for each element (σ_{tot}) are the quadratic sum of the individual parameter uncertainties and the uncertainty in the mean.

3 RESULTS AND DISCUSSION

In Table 2, we present the derived stellar abundances and their uncertainties (σ_{tot}). All of our derived abundances have uncertainties under ±0.1 dex, with most being $\leq$0.05 dex, with the exception of Kepler-411, a star in which many complications arose primarily due to it's cool temperature. Our sample of Kepler stars, all of which host potentially Earth-like planets, span a range of parameters (see Table 1 for more details). Further, the planets which orbit the stars are an adequate representation of the diversity of small planets, as they span an array of planetary sizes and densities. In addition, as can be readily seen in Table 1, our sample spans a broad range of metallicity, from subsolar to supersolar ([Fe/H] of -0.17 to +0.12), suggesting that small planetary systems are capable of forming in a wide range of metallicity. Our finding is consistent with Buchhave et al. (2012) who also finds that stars with small planets are capable of forming across a wide range of metallicities and can readily form throughout our Galactic disk. The abundances of our small planet hosts are contrary to the formation of giant planets, for which evidence strongly supports a high metallicity requirement in order for formation to occur. Without a particular metallicity requirement, we would expect small planet formation to be much more common than the formation of larger, Jupiter-like planet formation.

Stellar Abundances

The abundances of the galactic population are not randomly distributed and seem to follow well-defined trends, which is understood to be the result of Galactic chemical evolution. In Figure 2, we plot our abundances, in the form of [X/H], versus those of stars in the general Galactic population using data from Adibekyan and Bensby. We find that the stars with small planets are not distinguishable from the rest of the Galactic population as the derived abundances of our sample fall squarely within the well-defined Galactic trends. This leads us to suggest that small planet formation readily occurs around stars with typical Galactic compositions. This finding adds more evidence to the idea that small planet formation occurs differently than the formation of giant, Jupiter-like planets. Primarily, the efficiency of small planet formation appears to be much greater than the Jupiter-like planets. Whereas the Jupiter-like planets seem to require particular conditions to form, small planets appear to form in a much wider array of conditions. This higher efficiency suggests that, as hypothesized by Cassan et al. (2012), small planet formation is likely to be much more common throughout the Galaxy than the formation of giant planets. Indeed, recent studies suggest just that Borucki et al. (2011).

[2] σ_{μ}, uncertainty in the mean, is given by the equation

$$\sigma/\sqrt{N-1}$$

where σ is the standard deviation in the relative abundance of an element and N is the number of absorption lines measured for a given element.

Table 1. Stellar Parameters

Star	T_{eff} (K)	σ (K)	$\log g$ (cgs)	σ (cgs)	ξ ($\mathrm{km\,s^{-1}}$)	σ ($\mathrm{km\,s^{-1}}$)	[Fe I/H]	σ_μ	[Fe II/H]	σ_μ
Kepler-97	5875	±36	4.56	±0.08	1.39	±0.11	-0.17	±0.005	-0.17	±0.014
Kepler-128	6165	±53	4.25	±0.19	2.13	±0.23	-0.08	±0.007	-0.08	±0.017
Kepler-131	5791	±25	4.45	±0.11	1.36	±0.04	+0.12	±0.004	+0.12	±0.014
Kepler-411	4895	±53	4.58	±0.19	1.30	±0.23	+0.12	±0.012	+0.12	±0.037

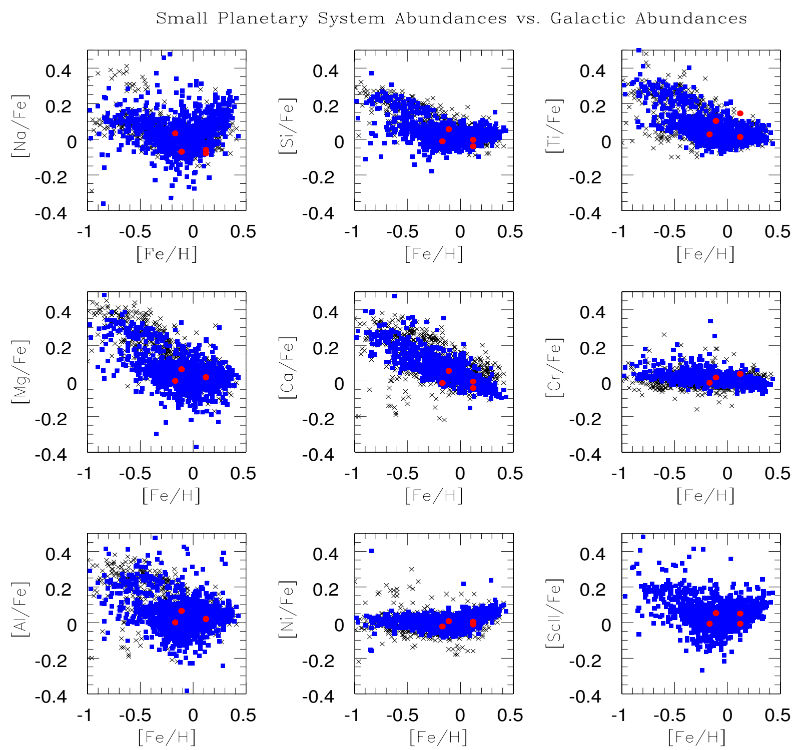

Fig. 2: Relative abundances as a function of metallicity. The derived abundances of our Kepler stars (red filled circles) are plotted with a large sample with stars in the general Galactic population taken from Adibekyan et al. (2012) (blue squares) and Bensby et al. (2014) (black crosses).

Our findings are in contrast to observations before the Kepler mission through which the scientific community had detected a large number of giant planets but extremely few small planets. Prior to the Kepler mission, the radial velocity method—where we look for changes in a star's motion due to gravitational effects which would indicate a planet's presence—was the primary method of planetary detection. The radial velocity method is more sensitive to larger planets as they create greater gravitational effects on a star. Consequently, giant planets were frequently discovered but few small planets were. The Kepler mission utilizes the transit method—in which planets are detected as they orbit in front of a star, causing a dip in the intensity of light we receive. With the transit method, we are less dependent on the planet's size. This, in conjunction with the telescope being outside of Earth's atmosphere, allows us to more easily detect the existence of small planets. Accordingly, observations are now strongly suggesting that small planets are more numerous in our Galaxy than giant planets. The present observations are in agreement with computational and theoretical findings that state small planet formation occurs more efficiently and across a wider range of conditions than the formation of giant planets. These findings fall in line with previous observations done (e.g. Buchhave et al., 2012; Cassan et al., 2012) that posit there is likely a greater population of smaller, Earth-like planets than there is of giant planets.

Table 2. Stellar Abundances

Star	Kepler-97	Kepler-128	Kepler-131	Kepler-411
C	-0.22 ±0.05	-0.04 ±0.06	0.04 ±0.05	0.72 ±0.21
O	-0.13 ±0.04	0.08 ±0.07	0.05 ±0.06	0.14 ±0.17
Na	-0.21 ±0.03	-0.04 ±0.03	0.12 ±0.02	0.10 ±0.11
Mg	-0.14 ±0.05	-0.05 ±0.03	0.18 ±0.02	-0.07 ±0.15
Al	-0.17 ±0.05	-0.05 ±0.02	0.14 ±0.03	0.14 ±0.07
Si	-0.18 ±0.02	-0.08 ±0.02	0.10 ±0.02	0.06 ±0.09
Ca	-0.13 ±0.03	-0.04 ±0.06	0.14 ±0.04	0.19 ±0.19
Sc II	-0.18 ±0.04	-0.04 ±0.07	0.11 ±0.05	0.17 ±0.14
Ti I	-0.13 ±0.04	-0.11 ±0.06	0.13 ±0.02	0.14 ±0.12
Ti II	-0.15 ±0.05	-0.13 ±0.09	0.14 ±0.04	0.15 ±0.14
V	-0.15 ±0.04	-0.11 ±0.05	0.16 ±0.02	0.17 ±0.16
Cr	-0.18 ±0.03	-0.09 ±0.04	0.16 ±0.02	0.14 ±0.10
Mn	-0.24 ±0.04	-0.21 ±0.05	0.16 ±0.05	0.08 ±0.10
Fe I	-0.17 ±0.02	-0.09 ±0.04	0.12 ±0.01	0.11 ±0.04
Fe II	-0.17 ±0.04	-0.09 ±0.08	0.12 ±0.05	0.11 ±0.21
Co	-0.19 ±0.04	-0.01 ±0.06	0.07 ±0.02	0.16 ±0.10
Ni	-0.19 ±0.02	-0.10 ±0.04	0.12 ±0.01	0.11 ±0.07
Zn	-0.22 ±0.03	-0.24 ±0.06	0.07 ±0.02	0.11 ±0.07

Is There Something Special about our Earth?

For the formation of giant planets, specific conditions in the protoplanetary disk must be met (e.g. Ghezzi et al., 2010b). Before the Kepler mission, we had essentially only known about these large planets as we did not have the capability of detecting smaller, terrestrial planets. Consequently, our predictions and models for small planet formation were based on what we knew about larger planet formation. This suggested that small planet formation did not readily occur throughout the Galaxy, but rather required the specific circumstances similar to giant planets. Now, as the Kepler mission has been highly successful at finding thousands of planetary candidates, we have the ability to further our understanding of small planet formation. There is a growing base of literature that is finding small planet formation readily occurring throughout the Galactic disk (e.g. Buchhave et al., 2012). Coupled with our most recent findings, the evidence suggests that small planet formation is ubiquitous throughout the Galaxy. The results of Cassan et al. (2012) led the authors to suggest that approximately 20% of Sun-like stars hosted a Jupiter-size planet. Whereas, 50% and 60% of solar analogs hosted a Neptune-sized or Super-Earth sized planet, respectively. They concluded that stars are orbited by planets as a rule, not an exception.

As our understanding of planetary formation continually grows, we find ourselves questioning the uniqueness of Earth. Fortunately, we now have a vast library of data to draw upon. This vast collection of data is increasingly supporting the idea that small planet formation readily occurs throughout the Galaxy. These findings are compounded by further research into the conditions of these smaller planets. One of the quirks of our solar system is that Earth is perfectly placed within the habitable zone, a zone in a planetary system in which a planet is close enough to receive ample light (energy) to support potential life, and have liquid water, but far enough away to remain at a temperature conducive to life and to avoid much of the more harmful radiation from the star. Any research into potential life-harboring exoplanets must take this idea of a habitable zone into account. Earth is incredibly well-suited to harbor life, present research is finding that it is not one of a kind. As it has already been shown that these small planets readily form throughout the galaxy, Petigura et al. (2013) examined whether or not any of these small planets exist within their respective habitable zone of their host stars. The authors found that 22% of Sun-like stars (of which conservative estimates claim there being around 10-20 billion in our Galaxy) have orbiting Earth-size planets within the habitable zone. From this, we are able to speculate that our special place in the Universe is not the exception to the way nature works. Rather, it is simply a consequence of the laws of physics.

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