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Compact Multi-planet Systems are more Common around Metal-poor Hosts

John M. Brewer[1,2], Songhu Wang[1], Debra A. Fischer[1], and Daniel Foreman-Mackey[3]
[1] Department of Astronomy, Yale University, 52 Hillhouse Avenue, New Haven, CT 06511, USA
john.brewer@yale.edu, songhu.wang@yale.edu, debra.fischer@yale.edu
[2] Department of Astronomy, Columbia University, 550 West 120th Street, New York, NY 10027, USA
[3] Flatiron Institute, 162 5th Avenue, New York, NY 10010, USA; dforeman-mackey@flatironinstitute.org
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Abstract

In systems with detected planets, hot Jupiters and compact systems of multiple planets are nearly mutually exclusive. We compare the relative occurrence of these two architectures as a fraction of detected planetary systems to determine the role that metallicity plays in planet formation. We show that compact multi-planet systems occur more frequently around stars of increasingly lower metallicities using spectroscopically derived abundances for more than 700 planet hosts. At higher metallicities, compact multi-planet systems comprise a nearly constant fraction of the planet hosts despite the steep rise in the fraction of hosts containing hot and cool Jupiters. Since metal-poor stars have been underrepresented in planet searches, this implies that the occurrence rate of compact multis is higher than previously reported. Due to observational limits, radial velocity planet searches have focused mainly on high-metallicity stars, where they have a higher chance of finding giant planets. New extreme-precision radial velocity instruments coming online that can detect these compact multi-planet systems can target lower-metallicity stars to find them.

Key words: planets and satellites: formation – stars: abundances – stars: solar-type

1. Introduction

The gas giant planet–metallicity correlation (Santos et al. 2004; Fischer & Valenti 2005) provided strong support for the core-accretion model (Pollack et al. 1996) over gravitational instability: massive cores should form more rapidly in more metal-rich (i.e., more massive) disks. Because the correlation is for giant planets on short period orbits, radial velocity searches made it possible to develop clean samples of stars with and without high-mass planets. As the number of discovered planets has exploded, we now know that almost all stars have planets (Howard et al. 2012; Burke et al. 2015; Winn & Fabrycky 2015), making it impossible to know if a given star is planet-free or simply has planets that evade our limited detection capabilities.

The search for extrasolar planets has identified two notable system architectures in the region close to the host star: multiple small planets on tight orbits, compact multi-planet systems (Lissauer et al. 2011), and massive planets on short orbits, hot-Jupiters. These two system architectures are almost mutually exclusive, with few hot-Jupiters having close companions and almost no compact multi-planet systems having nearby massive planets. Hot-Jupiters are uncommon, but occur more frequently around stars with high amounts of heavy elements (high metallicity; Santos et al. 2004; Fischer & Valenti 2005) but small planets can occur around stars with a wide range of metallicities (Buchhave et al. 2012, 2014; Wang & Fischer 2015; Petigura et al. 2018).

Compact multi-planet systems are mostly composed of planets near or below the current detection limits of radial velocity surveys. However, they tend to be very co-planar (Fabrycky et al. 2014), making them easy to detect in the *Kepler* transiting planet survey (Borucki et al. 2010). Some groups have looked at the average metallicity of these planets as a function of their radius, and found that smaller planets are found around stars with a lower average metallicity (Buchhave et al. 2014; Wang & Fischer 2015; Owen & Murray-Clay 2018). This hints that protoplanetary disks with less available solids may struggle to form larger planets, or even planets at all, but issues of selection bias and detection completeness still obscure a complete picture.

To circumvent these problems, we chose to look only at systems with detected planets and compare the properties of systems with unique architectures. Planet detection should not be biased toward a given type of system at a particular metallicity. We derived uniform stellar properties and elemental abundances from high-resolution spectra for almost 3000 stars, including almost 1200 planet hosts (Brewer et al. 2016; Brewer & Fischer 2018) and compared the number of systems of a given architecture to all known hosts as a function of the host metallicity. As stars evolve, the measured surface abundances of heavy elements can decrease (Dotter et al. 2017; Souto et al. 2018), which might bias any analysis of the influence of those elements on planet architecture. We limited our analysis to un-evolved stars ($\log g > 4.0$) and also looked at ratios of heavy elements to confirm our findings, as those ratios are relatively static over the main sequence lifetime of the stars.

2. Data and Analysis

2.1. Stellar Properties and Abundances

The stellar properties and abundances used in this Letter were all derived from high-resolution optical spectra taken with the Keck HIRES spectrograph and analyzed in a homogeneous manner (Brewer et al. 2016; Brewer & Fischer 2018). The analysis procedure has been shown to recover surface gravities consistent with those from asteroseismology to within 0.05 dex (Brewer et al. 2015) in addition to accurate temperatures and precise abundances for the abundances of 15 elements (C, N, O, Na, Mg, Al, Si, Ca, Ti, V, Cr, Mn, Fe, Ni, and Y). Statistical uncertainties for the abundances range from ~0.01 dex (iron and silicon) to 0.04 dex (nitrogen), depending on the element.

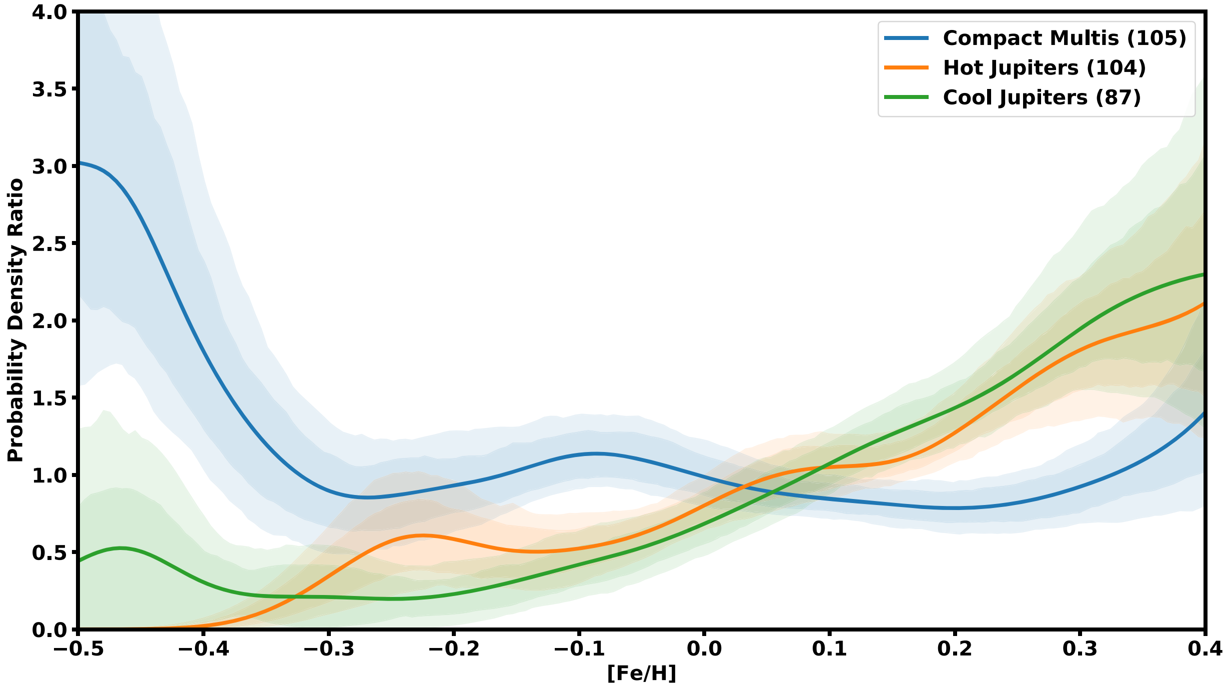

Figure 1. Frequency of compact multi-planet systems (blue) increases with decreasing metallicity as a fraction of known planet hosts. This is in contrast to hot-Jupiter systems (orange), which are assumed to be more frequent around higher metallicity stars as a consequence of the core-accretion model of planet formation. A comparison sample of cool Jupiters (green), systems with a giant planet on a wider orbit that may also include other planets, is more like the distribution of hot-Jupiter systems than the compact multi-planets, particularly at higher metallicities. The bold lines represent a Gaussian kernel regression to the distribution of metallicities of the specific architecture divided by the distribution for all known planet hosts. The shaded regions of the same color are 68% and 95% uncertainty intervals derived from fits to 200 bootstrap realizations of each distribution.

The parameters and abundances are derived using forward modeling performed with the analysis packages Spectroscopy Made Easy (SME; Piskunov & Valenti 2017), fitting in an iterative fashion. After continuum normalizing the spectrum and extracting 20 short wavelength segments totaling 350 Å between 5160 and 7800 Å, the initial temperature and gravity are set using broadband colors and the abundance pattern is set to that of the Sun. We then fit for the global stellar properties (effective temperature, surface gravity, rotational and Doppler broadening, metallicity) and the abundances of three α elements (Ca, Si, Ti) to allow for departures from the solar abundance pattern. Using the derived parameters from this first fit, we perturb the temperature by ±100 K and re-fit, taking the χ^2 weighted average as the global parameters from this stage. The global properties are then fixed, and we solve for the abundances of the 15 elements. This set of parameters and the abundance pattern are then used as a new starting point for a second iteration of the procedure.

The parameters and abundances are precise for dwarf stars of high signal-to-noise ratio (S/N), but trends in abundance with temperature have been identified for evolved stars and those with $\mathrm{S/N} < 45$. To avoid potential contamination, we removed all stars with $\mathrm{S/N} < 45$ and log surface gravities ($\log g$) < 4.0. The resulting combined catalog contains 1148 planets around 716 stars.

2.2. Planets and System Architectures

We cross-matched the stellar catalog with the confirmed planet catalog from the NASA Exoplanet Archive and adopted those planet parameters. We then defined three classes of exoplanet system architecture: hot Jupiters, cool Jupiters, and compact multi-planet systems. Hot-Jupiter systems are defined as having a planet with $M_{\text{planet}} > 0.5 M_{\text{Jupiter}}$ or $R_{\text{planet}} > 0.75 R_{\text{Jupiter}}$ and semimajor axis $\leqslant 0.3$ au, resulting in 104 hot-Jupiter systems. Cool Jupiters have the same mass or radius definition as hot-Jupiter planets, but have semimajor axes >0.3 au. This results in 87 cool-Jupiter systems. Finally, we defined compact multi-planet systems as having three or more planets orbiting at less than 1 au, resulting in 105 compact multi-planet systems. Only one hot-Jupiter system is also defined as a compact multi-planet system, and nine cool-Jupiter systems are in the compact multi-planet sample.

2.3. Planet Architecture Occurrence Analysis

To evaluate the relative occurrence rate of each system architecture as a fraction of known planet hosts at a given metallicity, we used Gaussian kernel density estimates (KDE) for the entire sample and each sub-population as a function of [Fe/H]. The optimum bandwidth was determined using Scott's rule (Scott 1979). From the KDEs we generated probability density functions (PDF) and then divided the PDF of each architecture by that of all known hosts. This gives us an estimate of the fraction of planetary systems of a particular architecture given the overall occurrence of discovered planetary systems as a function of metallicity. To visualize the uncertainties in these occurrence rates, we drew 200 bootstrap realizations from each of the architecture samples and performed the same procedure for these samples. We then calculated the 68% and 95% confidence regions over the entire metallicity range based on those bootstrap realizations.

3. Results

Comparing these planet architecture ratios, we find two opposing trends versus their log solar relative iron abundance,

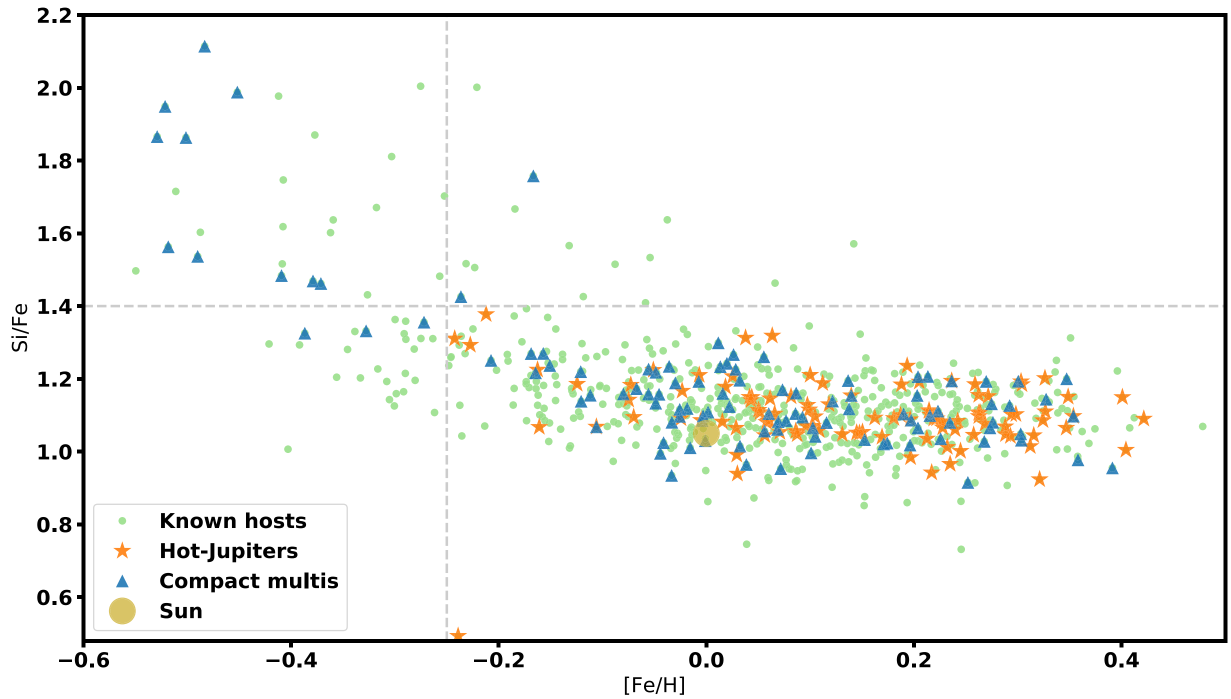

Figure 2. Stars with low metallicity or a high ratio of Si/Fe do not seem to form hot Jupiters, and are increasingly likely to host compact multi-planet systems. Plotted here are planet-hosting main sequence stars from our sample (green points), comparing the Si/Fe ratio to the log solar relative iron abundance, [Fe/H], with hot Jupiters (orange stars) confined to the lower right-hand side of the plot and compact multi-planet systems (blue triangles) making up a large fraction of the upper-left region. The Sun (yellow circle) is plotted for reference and the dashed lines are drawn to highlight the different populations. Stars with both high Si/Fe and high [Fe/H] are thought to be from the galactic thick-disk and are poorly represented in most planet search samples due largely to their greater distance.

or [Fe/H] (Figure 1). For hot Jupiters, we see the expected planet–metallicity correlation. The frequency of hot Jupiters increases with increasing metallicity. At the highest metallicities, the frequency of compact multi-planet systems also increases, but the frequency is also consistent with being almost flat from $-0.3 < [Fe/H] < 0.3$. However, at metallicities below -0.3 dex there is a sharp increase in the fraction of known planet hosts that are compact multi-planet systems, with a factor of three increase in the probability density over a range of just 0.2 dex.

Recent studies have suggested that cool Jupiters, giant planets residing more than 1 au from their host star, may be companions to compact multi-planet systems where large mutual inclinations prevent us from seeing one or the other (Morton & Winn 2014; Zhu et al. 2018). Due to their distance from their host star, it is more difficult to detect cool Jupiters through either radial velocities or transits, and as a consequence we are much less complete. However, it is instructive to compare their distribution to the other hosts to see if they are clearly associated with one or the other population. As a function of metallicity, cool Jupiters seem to closely trace the behavior of the hot-Jupiter systems and metallicities higher than ~ -0.3. The original planet–metallicity study included systems with planets on periods shorter than four years, which includes many cool Jupiters, so this result is not too surprising. However, for systems with $[Fe/H] < -0.3$, there is an increase in cool-Jupiter frequency similar to that of the compact multi-planet systems, although less strong and driven by the nine overlapping systems between the cool Jupiters and compact multis.

As a star ages, diffusion at the base of the convective zone can result in an apparent decrease in the amount of heavy elements at the stellar surface. The effect is more pronounced for more massive stars, but affects all elements heavier than helium roughly equally. Stars with lower initial metallicity should also have a higher ratio of α-elements to iron (Kordopatis et al. 2015), so we can use the Si/Fe ratio as a function of [Fe/H] to see if the increase in frequency of compact multis is due to age or inherently low metallicity (Figure 2). At both low metallicity and high Si/Fe, none of the hosts are hot Jupiters, and an increasing fraction are compact multi-planet systems. Low-metallicity stars in our sample have a higher Si/Fe, as expected for stars with initially low metallicity. The metallicity relation we see is not related to an observational bias caused by diffusion.

4. Discussion

Between $-0.3 < [Fe/H] < 0.4$, the fraction of systems that are compact multis stays relatively constant despite the steep increase in the fraction of hot and cool Jupiters. Compact multis are already known to be common around hosts of solar composition (Zhu et al. 2018). The increasing fraction of stars hosting compact multi-planet systems at lower metallicities points to a previously unrecognized reservoir of small-planet hosts. This has implications for planet formation models and may suggest that the these dynamically cool systems may form after the gas disk dissipates (Owen & Murray-Clay 2018). Previous studies have found evidence for two possible populations of planets, one with low mutual inclinations and low obliquities, and a second dynamically hotter one with fewer planets (Albrecht et al. 2013; Ballard & Johnson 2016). A separate study published while this Letter was being submitted also suggests that planet multiplicity may be tied to metallicity, with multi-planet systems more common around lower-metallicity stars (Zhu 2018), supporting our result.

Stars of lower metallicity and higher Si/Fe ratios are generally older or members of the galactic thick-disk population

(Kordopatis et al. 2015). This could point to a changing mix of planet architectures based on formation time and location. In fact, one of the oldest verified and low-metallicity planet hosts, Kepler-444, is home to a compact multi-planet system (Campante et al. 2015). New high-precision radial velocity surveys looking for Earth-massed planets (Jurgenson et al. 2016; González Hernández et al. 2017) may find a much larger population of small planets around these lower-metallicity stars.

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ORCID iDs

John M. Brewer https://orcid.org/0000-0002-9873-1471
Songhu Wang https://orcid.org/0000-0002-7846-6981
Debra A. Fischer https://orcid.org/0000-0003-2221-0861
Daniel Foreman-Mackey https://orcid.org/0000-0002-9328-5652

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