Investigating the Planet-Metallicity Correlation for Hot Jupiters

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ABSTRACT

We investigate the giant planet-metallicity correlation for a homogeneous, unbiased set of 217 hot Jupiters taken from nearly 15 years of wide-field ground-based surveys. We compare the host star metallicity to that of field stars using the Besançon Galaxy model, allowing for a metallicity measurement offset between the two sets. We find that hot Jupiters preferentially orbit metal rich stars. However, we find the correlation consistent, though marginally weaker, for hot Jupiters ($\beta = 0.71^{+0.56}_{-0.34}$) than it is for other longer period gas giant planets from radial velocity surveys. This suggests that the population of hot Jupiters probably formed in a similar process to other gas giant planets, and differ only in their migration histories.

Key words: Planetary Systems – stars: abundances – stars: fundamental parameters

1 INTRODUCTION

It only took the first few discoveries of giant exoplanets to notice that the host stars have a higher metallicity content compared with field stars hosting no planets (Gonzalez 1997; Santos et al. 2000, 2001) - Gonzalez (1997) proposed this link after just four giant planets were detected. This result has evolved into the now well-known giant planet-metallicity correlation; that is, the higher the metallicity of a star, the more likely it is to host a giant planet (Santos et al. 2004; Fischer & Valenti 2005; Johnson et al. 2010; Maldonado et al. 2012; Mortier et al. 2013; Schlaufman 2014). This result was recently reviewed by Adibekyan (2019), who reanalysed the giant planet-metallicity correlation using the homogeneous stellar parameters listed in the SWEET-Cat catalogue (Santos et al. 2013). They contrasted their sample of FGK dwarf hosts (with planets discovered by the RV and transit methods) with a comparison sample of FGK stars hosting no planets from the HARPS GTO program (see Adibekyan et al. 2012), which has stellar parameters derived using the same method as those in SWEET-Cat (thus making them directly comparable). They show a very obvious difference in the distribution of metallicity of stars without planets compared to stars hosting giant planets (see fig. 5 in Adibekyan et al. 2012), confirmed with a two-sample Kolmogorov-Smirnov (KS) test and reaffirming the existence of the giant planet-metallicity correlation.

When the giant planet-metallicity correlation was established, there were two main theories proposed as to why it occurs. The first, pollution or self-enrichment (suggested as the mechanism behind the correlation in Gonzalez 1997), suggests that the outer convective envelope of the star is polluted by an infall of material onto it, perhaps due to the inward migration of a gas giant planet. Primordial origin is the second: in this, the metallicity of the star is representative of the metallicity of the primordial cloud from which the star formed. This would imply that, in a high metallicity protoplanetary disc, giant planets form more easily. Santos et al. (2001) concludes that a simple pollution model cannot be the key process that leads to the metallicity offset of stars with planets, and primordial origin is further corroborated by results from Santos et al. (2003, 2004); Valenti & Fischer (2005, 2008); Johnson et al. (2010); and Maldonado et al. (2012). It is also supported by the core accretion planet formation theory (e.g. Ida & Lin 2004b), one of the leading theories of planet formation.

Core accretion (e.g. Pollack et al. 1996) is a bottom-up process, wherein the formation of giant planets begins with a rocky/icy core (10-15 M$_{\oplus}$); gas is then accreted onto the core in a runaway process until it has either cleared its orbit or the gas has been removed from the disk. If the initial disk has a higher metallicity content (i.e. more grains), it is expected that the large metal cores that go on to efficiently accrete gas would be more easily built, before the gas in the disk is lost. The planet-metallicity correlation is thus an important piece of observational evidence in support of this scenario. Core accretion timescales were thought to be longer than the lifetime of the disk, but have since been
found realistic when including disk evolution and migration (e.g. Rice & Armitage 2003; Albright et al. 2004). Adibekyan (2019) suggests that a combination of longer disk lifetime (e.g. Ercolano & Clarke 2010) and the presence of more material to form cores (e.g. Mordasini et al. 2012) that results from a higher metallicity protoplanetary disk can both influence the formation and migration of giant planets. Ida & Lin (2004a) and Benz et al. (2006) suggest that in a high metallicity environment, giant planets could form more efficiently (allowing more time for migration) and/or closer in to the star, potentially inside the snow line.

This study looks at the giant planet-metallicity correlation for a subset of giant planets on short period orbits: namely the “hot Jupiter” planets. The first discovery of an exoplanet around a main sequence star was the hot Jupiter 51 Peg b (Mayor & Queloz 1995), and since then they have been found in their hundreds. Despite being relatively easy to find with transit and radial velocity surveys, due to their large radii and short orbital periods, hot Jupiters are comparatively rare, with occurrence rates around FGK type stars of 0.4% (Cumming et al. 2008; Howard et al. 2012; Zhou et al. 2019).

We compare the giant planet-metallicity correlation of hot Jupiters to giant planets with longer periods, such as those found by the radial velocity surveys of Valenti & Fischer (2005) and Schlaufman (2014). Few papers have looked at the planet-metallicity correlation for hot Jupiters in particular, but some (sometimes contradictory) trends have been observed.

Sozzetti (2004) shows a lack of planets on very short period orbits (≤ 5 days) around stars with a metallicity less than solar, but due to potential biases and small-number statistics, cannot draw a clear conclusion. Some years later, with an increase in the number of hot Jupiter discoveries, Maldonado et al. (2012) found that at lower metallicities, hot giant planets are less frequent than their cool giant counterparts. Adibekyan et al. (2013) shows that planets (from 0.03M J to 4MJ) around metal-poor stars have longer periods. But Narang et al. (2018) observes that, while the average metallicity of the host star increases for orbital periods of less than 10 days when planets of up to 50M⊕ are present, there is no disparity between the average metallicity of stars hosting short (≤ 10 days) and long (> 10 days) period giant (> 50M⊕) planets.

Returning to Adibekyan (2019), it is now worth noting that a KS test shows the hosts of their separate radial velocity and transiting planet samples have indistinguishable metallicity distributions, despite the planets having significantly different orbital period regimes. Their transiting sample has an average orbital period of 11 days, whereas the average for their RV sample is 1202 days. Unfortunately, the average of the transit sample in Adibekyan (2019) is a little over the 10 day threshold that defines a short period giant planet in Narang et al. (2018), therefore making the two incomparable.

In this paper we begin in Section 2 by defining a sample of homogeneous transiting hot Jupiters that have been detected from wide-field, non-targeted, transit surveys. In Section 3 we compare this sample to a distribution of field stars drawn from the Besançon Galaxy model. In Section 4 we set out our findings in the context of the planet-metallicity correlation for hot Jupiters, and in Section 5 we discuss these results in the context of previous surveys and planet formation theory. Finally, we set out our conclusions in Section 6.

2 THE SAMPLE OF HOT JUPITERS

As their name suggests, hot Jupiters are exoplanets with masses and radii similar to Jupiter, but in very short (hot) orbits around their host stars. 51 Peg b (Mayor & Queloz 1995) is an archetypal hot Jupiter. The precise definition of a hot Jupiter varies a little in the literature; in this study we define it as an exoplanet with mass between 0.1 and 13M J (the upper limit being the approximate mass at which deuterium burning becomes possible; the lower limit ensures that the planets within the sample are gas giants and not terrestrial), and a period of up to 10 days (inclusive).

In order to probe whether the planet-metallicity correlation is different for hot Jupiters in comparison to longer period gas giants, we have compiled a sample of confirmed transiting hot Jupiters taken from the NASA Exoplanet Archive1 (Akeson et al. 2013). To ensure we have a sample free from any biases, we only select exoplanets which have been discovered from non-targeted surveys - i.e. from wide-field surveys where all stars within the field-of-view are searched. This naturally excludes any radial velocity discoveries, and also surveys such as *Kepler* (Borucki et al. 2010) and K2 (Howell et al. 2014), where only pre-selected stars were monitored. However, it does include the vast majority of hot Jupiter discoveries, and these discoveries have predominantly originated from the wide-field ground-based surveys: WASP (Pollacco et al. 2006); HATNet (Bakos et al. 2004); HATSouth (Bakos et al. 2013); KELT (Pepper et al. 2007); XO (Crouzet 2018); and TrES (Alonso et al. 2004). This unbiased sample is required in order to compare metallicity of hot Jupiter hosts to that of field stars drawn from a synthetic galaxy population such as Besançon. We also removed any hot Jupiter in a system with more than one star, either confirmed on the NASA Exoplanet Archive or suggested in its discovery paper, as previous literature has shown that stellar binaries (Eggenberger et al. 2004, 2011) and stellar multiplicity (Wang et al. 2014a,b) have an effect on planet formation (as summarised in Wang & Fischer 2015), and we did not wish to unintentionally bias the sample. Finally, we also exclude a small number of host stars with visual magnitudes of 9 or brighter, as for such systems we could not generate a large enough field stars distribution from the Besançon Galaxy model.

Our final sample consisted of 217 hot Jupiters, each with a corresponding host star. We present the properties of these hot Jupiters and their host stars in Figure 1 (left and right respectively), with parameters taken from the SWEET-Cat catalogue (Santos et al. 2013).

Metallicity is commonly expressed in terms of [Fe/H], which is the logarithm of the ratio of a star’s iron abundance compared with the Sun. The element iron is used due to strong, numerous, and easily measurable iron lines in the optical spectra of solar-type stars. We adopt [Fe/H] for this study, as it allows us to easily compile a homogeneous set of metallicities for our host stars, and it means

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1 https://exoplanetarchive.ipac.caltech.edu/
Figure 1. Properties of the 217 transiting hot Jupiters in our sample. Left: the hot Jupiter sample, displaying the mass and period selection criteria of 0.1 to 13 M\textsubscript{J} and up to 10 days respectively. Planet radius scales with the size of the marker (a larger marker indicates a larger radius), and equilibrium temperature scales with the marker colour (where yellow is hotter, and purple is cooler). Right: the metallicities and masses of the host stars of the hot Jupiter sample, with properties taken from SWEET-Cat. Similarly, star radius scales with marker size, and effective temperature with marker colour.

we can easily compare our work to previous studies. Metallicities for the hot Jupiter host stars were taken from the SWEET-Cat catalogue of stellar parameters (Santos et al. 2013), as this catalogue is the largest collection of host star and planet parameters that have been derived in a homogeneous way. SWEET-Cat utilises high resolution and high signal-to-noise spectra in deriving stellar properties, with a uniform methodology based upon the principles of iron ionisation and excitation equilibrium. Different groups use different analysis methods to derive their metallicities, which can introduce significant offsets - for example, Torres et al. (2012) shows that the difference in average metallicity calculated independently by the WASP and HATNet groups for a comparable samples of stars is about 0.17 dex. By using metallicity values solely from SWEET-Cat, we circumvent this issue.

3 ANALYSIS

3.1 Besançon simulation of field star populations

In order to determine if there is a correlation between the occurrence of hot Jupiters and host star metallicity, we need to determine the distribution of stellar metallicities from which the hot Jupiter host star was drawn. However, typically for a transit survey field, high resolution spectroscopy capable of determining metallicity is only undertaken on transiting planet candidates. This means that the overwhelming majority of stars in the transit survey do not have measured metallicities. It is therefore necessary to calculate the distribution of stellar metallicities from a simulated “field” star population from which our sample of hot Jupiter host stars was drawn. To make this simulation, we use the 2003 Besançon Galaxy Model (Robin et al. 2003), which provides the metallicity for individual simulated stars in [Fe/H] in a given parameter range (Robin et al. 1996).

We performed the default Besançon Catalogue simulation without kinematics, using the Johnson-Cousins Photometric system. We created a population of simulated stars for each individual hot Jupiter host star, with a range of galactic latitude and longitude within 10 deg\textsuperscript{2} of the hot Jupiter host star. The simulated population was restricted to stars with a visual magnitude with \(\Delta m_{\text{mag}} = 1\) of the hot Jupiter host star. We further restricted the population to dwarf stars, which removed distant giants for which transit surveys were not sensitive to finding hot Jupiters around. Finally, we restricted the population to the mass range of the host star sample, from 0.52 to 1.6 M\textsubscript{\odot}, in order to remove very high mass stars, which again transit surveys were not sensitive to finding hot Jupiters around. All other Besançon Galaxy Model parameters were kept to the default values, as these have been shown to best simulate stellar populations in our local Galaxy when compared with large spectroscopic surveys (Nandakumar et al. 2017). For each of our 217 hot Jupiter host stars, we selected 50 stars from the corresponding simulated stellar populations which were closest in visual magnitude value to the hot Jupiter host star. Thus our final set of simulated stellar populations comprised of 10850 stars in total.

In order to examine whether our simulated stellar populations accurately represent our sample of hot Jupiter host stars, we make a comparison of the stellar mass distributions of each - see Figure 2. Performing a KS test on the two distributions returns a statistic of 0.071 and a p-value of 0.23, indicating that the masses of the hot Jupiter host stars are likely to be drawn from the same population as the simulated Besançon stellar population. This gives us confidence that the simulated Besançon population does represent the stellar population from which the hot Jupiter host stars are drawn.

3.2 The planet-metallicity correlation

In the seminal work on the planet-metallicity correlation of Valenti & Fischer (2005), it was shown that the probability of finding a giant planet rises sharply as a function of the metallicity of the star. Valenti & Fischer (2005) utilises a
in Equation 2 using the MCMC sampler emcee (Foreman-Mackey et al. 2013). The log of the p-value output of the KS test was taken as the log likelihood at each step in the chain - we are maximising the p-value as a higher p-value indicates that the values for $\beta$ and $c$ are a better fit.

After a preliminary search over the $\{\beta, c\}$ parameter space, uniform priors were placed on both $\beta$ and $c$, but they were restricted to the ranges $0 \leq \beta \leq 1.8$ and $0 \leq c \leq 0.2$. This process was run for 5000 steps after an initial 500 that were discarded as burn-in. The results are set out in Section 4 below.

4 RESULTS

We find that for our uniform sample of 217 hot Jupiters, there is a clear difference in metallicity between our hot Jupiter host stars and the simulated field star comparison sample. Figure 3 displays the metallicity distributions for our simulated field stars (in red) compared to our hot Jupiter host stars (in blue). The histograms are clearly distinct in terms of their distributions, with the simulated field stars being less metal-rich than the hot Jupiter hosts. Specifically, the mean metallicity of the simulated field stars is $[\text{Fe/H}]=0.115 \pm 0.003$ dex, while the hot Jupiter host stars is $[\text{Fe/H}]=0.100 \pm 0.012$ dex, where the error is given as the standard error of the mean. This gives a significant metallicity difference of 0.215 dex. A KS test comparing the distributions gives a statistic of 0.35 and a p-value of $1.47 \times 10^{-23}$, allowing us to reject the null hypothesis: these 2 samples are not drawn from the same population.

The exploration of the $\{\beta, c\}$ parameter space allows us to disentangle the degree to which this metallicity difference is due to a systematic metallicity offset between SWEET-Cat and Besançon, or an intrinsic planet-metallicity correlation for hot Jupiters. Figure 4 shows the corner plot of the $\{\beta, c\}$ parameter space described in Section 3. From these samples, we estimate values for $\beta$ and $c$ of $0.71^{+0.56}_{-0.34}$ and $0.104^{+0.026}_{-0.033}$ respectively. These were estimated using the 16th, 50th, and 84th percentiles.

In Fig. 3 we show the expectation for the metallicity distribution of the simulated field stars weighted as if they all hosted hot Jupiters (black outline) - i.e. applying Equation 2 with our best fit $\beta$ and $c$ from the MCMC exploration ($\beta = 0.71, c = 0.104$). We see the weighted sample distribution closely approximates the hot Jupiter host star distribution. The KS test result for the weighted sample distribution with the best fit values of $\beta$ and $c$ gives a statistic of 0.062 and a p-value of 0.838. This shows that this distribution and the hot Jupiter host star distribution are indistinguishable.

5 DISCUSSION

Our key result is that hot Jupiters show a planet-metallicity correlation that follows a power law with $\beta = 0.71^{+0.56}_{-0.34}$. In this Section we compare this to previous studies, examine any potential biases in our statistic sample, and discuss the implications of our results in terms of the formation and migration of hot Jupiters.
5.1 Comparisons with previous studies

Valenti & Fischer (2005) studied a sample of 1040 FGK stars from a long-term, homogeneous radial velocity survey, and found that $\beta = 2$ in the regime of giant planets with orbital periods $< 4$ years. No uncertainties are placed on their result.

Johnson et al. (2010) also studied the giant planet-metallicity correlation, this time for a sample of 1194 stars covering a wider stellar mass range of AFGKM stars drawn from a combination of the Keck M Dwarf Survey, the original SPOCS catalogue from Valenti & Fischer (2005), and the SPOCS IV catalogue. They found a value of $\beta = 1.2 \pm 0.2$, which is slightly higher but fully consistent with our result.

Schlaufman (2014) used a sample of 620 FGK stars, 44 of which host at least one giant planet, from the HARPS GTO program (taken from Adibekyan et al. (2012)), using logistic regression to derive a $\beta$ value of $2.3 \pm 0.4$. Interestingly, this result is in good agreement with the Fischer & Valenti (2005) result, but not with the result of Johnson et al. (2010) or with our result.

While all of the above results are from radial velocity surveys, there have also been previous attempts to calculate $\beta$ from transit surveys, in particular from the Kepler survey (Borucki et al. 2010). Guo et al. (2017) and Petigura et al. (2018) both evaluate $\beta$ for the population of 14 hot Jupiters in the Kepler data. Guo et al. (2017) find a value of $\beta = 2.1 \pm 0.7$, consistent with radial velocity results, while Petigura et al. (2018) find a value of $\beta = 3.4^{+0.9}_{-0.8}$, which is higher than previous studies. The low number of hot Jupiters from Kepler, coupled with the complex targeted nature of the survey (c.f. the untargeted surveys used in our sample), means that these results need to be approached with some caution.

Our result ($\beta = 0.71^{+0.56}_{-0.34}$) confirms the giant planet-metallicity correlation seen in previous studies, but suggests...
that it is marginally weaker for hot Jupiters than it is for the longer period giant planets such as in the survey outlined above. We summarise our result and the previous results in Table 1.

Our $\beta$ value is lower than all previously published results in Table 1. We are within 1σ of the result of Johnson et al. (2010); however, if we accounted for the mass dependency in our calculation as they have, we would expect our value for $\beta$ to decrease further (though not significantly so, as the stellar masses in our sample have a range of only $\approx 1M_\odot$). We are 2.32 and 2.31σ from Valenti & Fischer (2005) and Schlaufman (2014), the two other results from RV surveys, respectively. While these hint at a difference in the strength of the correlation between cool and hot Jupiters, we are also 1.55σ removed from Guo et al. (2017), and 2.75σ from Petigura et al. (2018), the two hot Jupiter specific studies. Though again it should be noted that both hot Jupiter studies have a very small sample size.

5.2 Potential biases

The metallicity offset ($c$) is needed to calibrate between the metallicities in Besançon and SWEET-Cat, but adds an extra degree of uncertainty compared with a survey that has a uniformly determined set of metallicities for both hot Jupiter hosts and field stars. However, the metallicity offset appears fairly well constrained from the sample distribution in Fig. 4, and is relatively small in comparison to the overall spread of metallicities (c.f. Fig. 3). The metallicity offset does correlate with $\beta$ (see Fig. 4), which results in a relatively large and slightly asymmetric uncertainty on $\beta$.

There is also a correlation between the radius of a star and its metallicity; the increase in opacity with the presence of metals results in the star having a larger radius. As transit depth decreases with the square of a star’s radius, planets would be more difficult to detect around higher metallicity stars via the transit method. This would act to decrease our value of $\beta$, but it has been found by Petigura et al. (2018) that planet detectability does not significantly depend on stellar metallicity.

RV surveys will preferentially find planets around metal rich stars as it is easier to perform the method when there are stronger and/or more metal lines present in the host star spectra. We do not expect the detection of a planet via the transit method to depend significantly on metallicity of the host star - and this is one of the advantages of using a sample of hot Jupiter planets from transit survey discoveries. However, it should be noted that confirmation of planets from transit surveys is based on RV follow-up, which will still be subject to the bias described above.

5.3 Hot Jupiter Formation and Migration

Hot Jupiters were an unexpected discovery, given how close-in they are to their host stars and that they have no solar system analogue. Due to the lack of disk mass close to a star, in-situ formation was thought to be unlikely; instead, it has been posited that hot Jupiters form far out from their star, beyond the snowline, and then undergo inward migration after or during their formation. Core accretion, supported by the planet-metallicity correlation, together with disk-driven migration and interactions with planetary companions when the hot Jupiter is misaligned with the stellar rotation axis (e.g. Dawson & Murray-Clay 2013) are currently thought to be the main mechanisms producing hot Jupiters. In-situ formation has, however, been recently reconsidered to be a possibility (e.g. Boley et al. 2016).

Maldonado et al. (2018) makes the assumption that hot and cool Jupiters would have similar chemical properties if hot Jupiters were formed at large distances from their star and then migrate inwards, but they find that hot and cool Jupiters have different properties, and that they are two distinct populations. Perhaps they have different formation methods, or perhaps hot Jupiter migration is a metallicity dependent process. Maldonado et al. (2018) argues that the latter is unlikely, as it would not be expected that migration would change the abundance of the host star.

A number of studies examine the relationship between metallicity of a host star and the orbital period of different planet types in the system, including giant planets. The result of Narang et al. (2018) finds no difference in metallicity with orbital period for giant planets. Adibekyan et al. (2013) find that, from $\sim 10 M_\oplus$ to $\sim 4 M_\oplus$, planets in metal-poor systems have longer periods than those in metal-rich systems. They suggest this may be due to planets in a metal-poor disk forming further out and/or undergoing later and thus less migration as they take longer to form. Mulders et al. (2016) finds that, while occurrence rate of hot rocky exoplanets within a 10 day orbital period increases with metallicity, hot gas giants exhibit no significant relationship between metallicity and orbital period.

Our result that hot Jupiters preferentially orbit metal-rich stars is in agreement with all past results on the planet-metallicity correlation, and is more evidence towards the core accretion model of formation. As our value for $\beta$ is consistent with past RV survey results (though marginally weaker), it suggests that hot and cool Jupiters may form in the same way, and that their migration is different. The nature of this correlation might be an indication against in-situ formation - you would expect in-situ formation to be enabled by higher amounts of metals compared to systems which form planets further out, but our result does not indicate a comparative increase in the metallicity of hot Jupiter systems over longer period gas giants.
6 CONCLUSION

We have examined the giant planet-metallicity correlation using the host stars of hot Jupiter planets, based on a sample of 217 hot Jupiters taken from the transit surveys WASP, HATNet, HATSouth, KELT, XO and Tycho, with metallicities taken from SWEET-Cat. We compare these to a population of field stars simulated with the Besançon Galaxy model, and find a clear difference in their metallicity distributions, with the hot Jupiter hosts being more metal rich. We use the formalism of Valenti & Fischer (2005) (Equation 1) and find $\beta = 0.71^{+0.56}_{-0.34}$. This result is lower, but consistent to within uncertainties, to $\beta$ values derived from radial velocity surveys that probe much longer period giant planets (e.g. Valenti & Fischer 2005; Johnson et al. 2010). We conclude that this is strong evidence to suggest that the population of hot Jupiter giant planets is not a distinct population, but is drawn from the same population as giant planets on longer orbital periods. This result will be able to be confirmed by the complete set of hot Jupiter planets orbiting bright stars that should arise from the TESS mission (Ricker et al. 2015), in conjunction with a more complete and consistent survey of stellar metallicities.

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