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Investigating the Planet-Metallicity Correlation for Hot Jupiters

by

Ares Osborn

Thesis

Submitted to the University of Warwick

for the degree of

MSc by Research

Department of Physics

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Declarations

I declare that the work in this thesis is my own and was carried out at the University of Warwick, during the period October 2018 to October 2019, under the supervision of Dr. Daniel Bayliss. The research reported here has not been submitted, either wholly or in part, in this or any other academic institution for admission to a higher degree.

The work in this thesis has been submitted for publication in the Monthly Notices of the Royal Astronomical Society (MNRAS) on 8 October 2019.

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Abstract

I 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. I 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. I find that hot Jupiters preferentially orbit metal rich stars. However, I 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.

Abbreviations

 ${\bf RV}\,$ Radial Velocity

 $\rm R_\oplus\,$ Earth radius, $6\,378\,\rm km$

 ${\bf KS}~{\bf Test}$ Kolmogorov-Smirnov Test

- MCMC Markov-Chain Monte Carlo
 - **TESS** Transiting Exoplanet Survey Satellite
 - $M_\oplus\,$ Earth mass, $5.972\times 10^{24}\,\rm kg$

- $M_{\rm J}\,$ Jupiter mass, $1.898\times 10^{27}\,\rm kg$
- $R_{\rm J}\,$ Jupiter radius, $71\,492\,\rm km$
- $M_\odot~Solar$ mass, $1.989\times 10^{30}\,\rm kg$
- $\rm R_{\odot}~Solar~radius,\,695\,700\,km$

Chapter 1

Introduction

1.1 Exoplanets

We have been thinking about what is out there for centuries. Are there other planets like ours? Are we alone in the Universe, or is there life out there, like us?

We have known about the other planets in our Solar System for a long time; many are visible to the naked eye in the night sky. Early speculation about planets other than those in our Solar System is documented from the sixteenth century; Italian philosopher Giordano Bruno believed that the stars in the sky might be like our own Sun, with their own planets (Bruno, 1584).

It is only recently, however, that we have actually discovered these planets around other stars - extra-solar planets, or "exoplanets" as we call them now. The first confirmed discovery of an exoplanet was made by Wolszczan and Frail (1992): two planets were discovered around a pulsar star, and then a third in the same system was found several years later (Wolszczan, 1994). A pulsar is a rapidly rotating neutron star that emits a beam of electromagnetic radiation; this flashes into view during each rotation (like a lighthouse) on a regular period. Neutron stars are an end product of a supernova, so to find planets around one is remarkable - their formation must have occurred after the supernova, as any planets formed before would likely have been destroyed or ejected from the system.

These first detections have ushered in an age of amazing discoveries, and research has progressed at an astounding rate. So far there have been over 4000 confirmed exoplanet discoveries, according to the NASA Exoplanet Archive¹ (Akeson et al., 2013). Our sample size of exoplanets is now sufficiently large, due to the results of space-based surveys searching for planets such as *Kepler* and *TESS*,

¹https://exoplanetarchive.ipac.caltech.edu/

that we can begin to make inferences about the typical number of planets around different types of stars, and of the occurrence rates of planets of different sizes (e.g. Fressin et al., 2013; Zhou et al., 2019).

We have learnt that exoplanets have extraordinary diversity: some are similar to our Earth and the other planets in the Solar System, but many are wildly different with no Solar System analogues. We have found rocky planets similar to our own, but twice the size ("super Earths") (e.g. Gandolfi et al., 2018; Huang et al., 2018); we have found systems of up to 7 planets, such as TRAPPIST-1, with all of their planets tightly packed on orbits shorter than that of Mercury (Gillon et al., 2016, 2017); and we have even found massive planets the size of Jupiter, so close to their stars that their orbital periods are a matter of days ("hot Jupiters") (e.g Mayor and Queloz, 1995; Charbonneau et al., 2000; Bouchy et al., 2005). Many questions still remain about these systems, so unlike our own Solar System, and the existence of hot Jupiters have raised their fair share.

1.2 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. It is relatively common for hot Jupiters to have equilibrium temperatures of ~2000 K; KELT-9b is as hot as a K dwarf star at over 4000 K (Gaudi et al., 2017). The precise definition of a hot Jupiter varies a little in the literature; in this study I define it as an exoplanet with a mass between 0.1 and 13 M_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).

Otto Struve posited that planets might exist at very small distances from their stars, as stellar companions had already been found this close. He derived that a planet the size of Jupiter might just about be detectable via the Doppler effect with the most powerful spectrograph of the time, and detection of bigger super-Jupiters would be easier. He suggests that eclipses of the star by the planet ("transits") might also be detectable (Struve, 1952). This theory came 40 years before the first confirmed exoplanet discovery.

Despite Struve's view, planetary formation theories of the time, based primarily on the Solar System, envisaged that giant planets formed far out from their host stars (Pollack et al., 1996), and so the discovery of hot Jupiters was met with some surprise. The first planet that was found around a solar type star, 51 Peg b,



Figure 1.1: The cumulative detections of exoplanets, binned into years, and broken down by detection method. Discoveries are dominated by transit (green) and RV (red) detections. *Image credit: NASA Exoplanet Archive.*

is an archetypal hot Jupiter (Mayor and Queloz, 1995), and since that discovery they have been found in their hundreds. Despite being relatively easy to find with transit and radial velocity surveys (discussed in Section 1.3) due to their large radii and short orbital periods, hot Jupiters are now known to be rare in comparison to smaller sub-Neptune and Earth-sized planets, with occurrence rates around FGK type stars of 0.4% (Cumming et al., 2008; Howard et al., 2012; Zhou et al., 2019).

Transiting hot Jupiters also dominate the planets that can have their atmospheres studied via transmission and emission spectroscopy, and there have been discoveries of several atomic and molecular species in their atmospheres (e.g. Charbonneau et al., 2002; Swain et al., 2009; Evans et al., 2016).

1.3 Exoplanet Detection Methods

Exoplanets are incredibly faint compared to their host stars, with an almost negligible separation on the sky of a few arcseconds at most. Direct detection becomes very difficult due to these factors, and while it has been met with some success (Marois et al., 2008, 2010), it is currently only possible for young (and therefore still hot and luminous), massive planets at a large orbital separation from their host star. Thus the vast majority of exoplanet detections have been through what we call "indirect" methods, inferring a planet's existence from the effect it has on its host star. As can be seen in Figure 1.1, by far the two most prolific methods have been the radial velocity and transit methods, the underlying principles of which are summarised below.

1.3.1 The Radial Velocity Method

The bodies in a planetary system orbit a common centre of mass, called the barycentre. If you have a simple system of a single planet orbiting a star (as in Figure 1.2), the star has a relatively small orbit around the barycentre, but this motion results in a periodic change to observable qualities of the star, the most commonly measured of which is its radial velocity (RV), its velocity directly towards or away from the viewer. This is measured from precise stellar spectra taken many times over the entire orbital period of the planet. The spectrum of a star will exhibit a Doppler shift depending on whether the star is moving towards (blue-shifted) or away (redshifted) from the viewer, the magnitude of which increases if the radial velocity is higher. Larger planets on shorter orbits (like hot Jupiters) induce larger changes in the radial velocity of their host stars, and so are relatively easier to detect by this method in comparison to smaller, more distant planets. From RV measurements, you can estimate the minimum mass of the planet, its period, semi-major axis, eccentricity, and make an estimate of potential transit times.

So far we have discovered 794 planets via RV measurements, as of September 2019 (NASA Exoplanet Archive). Current spectrographic capabilities, such as those of HARPS, allow us to observe RVs down to $\sim 1 \text{ m s}^{-1}$ (Mayor et al., 2003). This is precise enough to allow us to find hot Jupiters - typically, a star hosting a hot Jupiter will have a radial velocity on the order of hundreds of m s⁻¹. However, in order to detect an Earth-like planet around a Sun-like star, we need to be able to detect RVs on the order of 10 cm s^{-1} , which is the aim of the next generation of spectrographs such as ESPRESSO (Pepe et al., 2010).

1.3.2 The Transit Method

The transit method relies on the orbital plane of a system to align with the line of sight of the viewer. For the viewer, the planet will then be between their line of sight and the star, blocking some of the light from the star as the planet moves across its face as shown in Figure 1.3. If you assume the radius of the planet, R_p , is small in comparison to the radius of its host star, R_* , and that the orbit of the planet is



Figure 1.2: The RV detection method. Top: a planet and star orbit the barycentre of the system, marked by a cross. The motion of the star due to the planet can be seen in the Doppler-shifted light reaching an observer on Earth. Bottom: Fig. 4 from Hebb et al. (2009), the RV curve of WASP-12 from SOPHIE. The solid line indicates the best fit model to the data resulting from an MCMC analysis to retrieve the orbital parameters of the system. WASP-12 hosts the hot Jupiter planet WASP-12b.



Figure 1.3: The transit detection method. Top: as a planet passes between the face of its star and the line of sight of an observer, a corresponding dip in the stellar flux can be detected. This has a characteristic shape, with sloped sides (b to c; e to f) when the planet is not fully overlapping the face of the star, and a curved bottom (d) caused by limb darkening of the star. Bottom: Fig. 4 from Močnik et al. (2018), the phase-folded light curve of WASP-104 from K2 (bottom panel), where the red line indicates the best-fit model. The residuals of the fit are shown in the top panel.

circular with semi-major axis a, then the probability of an alignment favourable for transit observations, p, is given by (Borucki and Summers, 1984):

$$p = \frac{R_*}{a}.\tag{1.1}$$

This is small, but fortunately planets with a small separation from their star have proven plentiful. To increase the chance of finding planetary signals, transit surveys tend to have a relatively large fields of view, in order to study many stars at once.

The dimming in the star's light occurs periodically with the orbital period, and the planet blocks a certain percentage of the star's light depending on the radius of the planet compared to the star. The depth of the transit, d, is given as:

$$d = \left(\frac{R_{\rm p}}{R_*}\right)^2,\tag{1.2}$$

which is again small. For example, a Jupiter-size planet transiting a Sun-like star blocks ~1% of the light of its star; an Earth-size planet transiting a Sun-like star blocks ~0.01%. The transit method is strongly biased towards larger planets (R_p^3) , with more luminous stars $(L_*^{3/2})$, and smaller semi-major axes $(a^{-7/4})$ (Haswell, 2010).

If the radius of the star is known prior, we can find the radius of the planet from its transit depth (Equation 1.2). Together with a mass determination, often obtained from Doppler measurements described previously in Section 1.3.1, the mean density of the planet can be estimated informing us about the make-up of the planet's interior. Our best planet characterisations come from planets that are amenable to both transit and RV measurements, as transits cannot yield a mass measurement but RVs can, while RVs cannot yield a radius measurement but transits can. It is also worth noting that many of the derived planet properties depend on prior determination of the properties of their host star; as such, it is also incredibly important to have accurate stellar parameters to give accurate planetary parameters.

The first observations of a transiting exoplanet were made when observing HD 209458 (Henry et al., 2000; Charbonneau et al., 2000), a system already known from RVs to host a hot Jupiter. It was the first indication of a hot Jupiter having a radii and density similar to that of the Solar System gas giants.

Following this discovery, other known RV systems were monitored for transits, and transit surveys from the ground and then space were subsequently set up. These are usually wide-field surveys, monitoring large patches of the sky to find planets from periodic transits across stars. Prolific ground-based surveys include HATNet (Bakos et al., 2004) and Super-WASP (Pollacco et al., 2006). The *Kepler* spacecraft was launched in March 2009, and its surveys, *Kepler* (Borucki et al., 2010) and K2 (Howell et al., 2014), have had 2345 and 389 confirmed planet discoveries respectively. More recently, the spacecraft *TESS* finished its first year of observations in August 2019, and so far has 29 confirmed planets, with another year of observations to follow. As of September 2019, 3137 confirmed planets have been discovered initially by a transit detection (NASA Exoplanet Archive).

1.4 Metallicity Measurements of Stars

Information can be deduced about how planetary systems form from the connection between their properties and the properties of their host stars: for example, the metallicity of a star reflects the metallicity of the protoplanetary environment from which planets form.

A common measure of metallicity is to compare the iron content of a star to its hydrogen content, where N_{Fe} and N_H are the number of iron and hydrogen atoms in a unit volume respectively. The abundance ratio is the logarithm of this compared to the Sun:

$$[Fe/H] = \log_{10} \left(\frac{N_{\rm Fe}}{N_{\rm H}}\right)_{star} - \log_{10} \left(\frac{N_{\rm Fe}}{N_{\rm H}}\right)_{sun},\tag{1.3}$$

the unit of which is the "decimal exponent," or dex. The Sun therefore sets the benchmark for this scale with a metallicity of 0. [Fe/H] is positive for stars with higher metallicity than the Sun, where a value of +1 is 10 times the metallicity of the Sun; [Fe/H] is negative for stars with lower metallicity than the Sun, where a value of -1 is 1/10 times the metallicity of the Sun. The element iron is used due to strong, numerous, and easily measurable iron lines in the optical spectra of solar-type stars.

1.4.1 The Planet-Metallicity Correlation

It only took the first few discoveries of giant exoplanets to notice that their 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 and Valenti, 2005; Johnson et al., 2010; Maldonado et al., 2012; Mortier et al., 2013; Schlaufman,



Figure 1.4: Fig. 5 of Adibekyan (2019), showing the metallicity distributions of giant planet hosts from RVs (pale blue), from transits (mid blue), and of field stars (red). Their cumulative distribution functions are over plotted as lines in the corresponding colours. While the distributions for the giant planet hosts are similar, despite the different detection methods, they are both offset to higher metallicities in comparison to the field stars.

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 star 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. 1.4, reproduced from Adibekyan 2019), confirmed with a two-sample Kolmogorov-Smirnov (KS) test (see Section 2.1.1) and reaffirming the existence of the giant planet-metallicity correlation.

1.4.2 Links to Giant-Planet Formation Theory

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 and 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 and 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 and Armitage, 2003; Alibert et al., 2004). Adibekyan (2019) suggests that a *combination* of longer disk lifetime (e.g. Ercolano and 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 and 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.

The second theory proposed for planet formation is gravitational instability (e.g. Boss, 1997, 2006), a top-down process in which giant planets form from the gravitational collapse of a protoplanetary disk. It has the advantage of a shorter timescale for planet formation in comparison to core accretion; planets can form in thousands of years for the former. Unfortunately, this scenario does not explain the observed planet-metallicity correlation - here, planet formation efficiency would not be expected to have a dependence on metallicity (Boss, 2002). In fact, it has been shown by Meru and Bate (2010) and Rogers and Wadsley (2012) that as metallicity decreases (at low disk opacity), gravitational instability may be *more* likely to form giant planets, and this is in direct contrast to the observed planetmetallicity correlation.

These theories, however, are not necessarily mutually exclusive, and it might be the case that core accretion is more efficient in some parameter spaces, and gravitational instability in others. It has been found that the giant planet population itself may have different metallicity regimes depending on the mass of the planet: for example, Santos et al. (2017) shows that giant planets may be split into two distinct populations, less and greater than $4M_J$, with the latter having host stars that are, on average, more metal-poor. Narang et al. (2018) also finds that above $4M_J$, average host star metallicity decreases, and suggests this is perhaps indicative of a different formation mechanism for "super" Jupiters. Mortier et al. (2013) suggests that gravitational instability could dominate in the metal poor regime, while core accretion dominates in the metal-rich; however, they point out that there is currently still an issue of small sample size in the low metallicity regime.

1.4.3 The Planet-Metallicity Correlation for hot Jupiters

This study looks at the giant planet-metallicity correlation for a subset of giant planets on short period orbits: namely the hot Jupiter planets described in Section 1.2.

I 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 and 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 $4M_J$) around metal-poor stars have longer periods. But Narang et al. (2018) observes that there is no disparity between the average metallicity of stars hosting short (≤ 10 days) and long (> 10 days) period giant (> 50 M_{\oplus}) 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.

Chapter 2

Methods & Analysis

2.1 Analysis Methods

In order to draw comparisons between hot Jupiter host stars and field stars, and then between the planet-metallicity correlation for hot Jupiters and past literature results, I primarily utilise the following two analysis tools.

2.1.1 The KS Test

A Kolmogorov-Smirnov (KS) test is used to compare one-dimensional probability distributions - i.e. it is a test of how similar the probability distributions are. The one-sample test compares an observed sample to a reference distribution; the twosample test compares two observed samples to each other. I focus on the latter in this report, as a way to compare the similarity of the metallicity distributions of field stars and hot Jupiter host stars.

The two-sample KS test compares the two samples via their empirical distribution functions ($F_{1,n}$ and $F_{2,m}$), where the empirical distribution function is an estimate of the cumulative distribution function of a sample from empirical measurements of the sample. If you plot the distribution functions (e.g. Figure 2.1), the KS test statistic, D, is the maximum vertical difference between the two distributions. This can be expressed as:

$$D_{n,m} = \sup_{x} |F_{1,n}(x) - F_{2,m}(x)|, \qquad (2.1)$$

where **sup** is the supremum function - this finds the maximum output of the original set of functions for every input in the domain, and so it is finding the maximum difference between the two distributions.



Figure 2.1: The two-sample KS test, where the red and blue lines correspond to the empirical distribution functions of two different samples. The statistic is shown as the black arrow. *Image credit: Bscan, Wikimedia Commons.*

The null hypothesis for this test is that the two samples are drawn from the same distribution. In general, if the KS statistic is small or the p-value is high, then the null hypothesis (that the two samples have the same distribution) **cannot** be rejected. Conversely, if the p-value is small, then the null hypothesis **can** be rejected. Quantitatively, the null hypothesis can be rejected if:

$$D_{n,m} > c(\alpha) \sqrt{\frac{n+m}{nm}}, \qquad (2.2)$$

where *n* and *m* are the sizes of the samples, and α is the confidence level (a 90% confidence corresponds to an α value of 0.10, 95% to 0.05, and so on). Computing $c(\alpha)$ can be done with the general equation:

$$c(\alpha) = \sqrt{-\frac{1}{2}\ln\alpha}.$$
(2.3)

2.1.2 MCMC

In order to explore the form of the planet-metallicity correlation, I employ a Markov-Chain Monte Carlo (MCMC) method. MCMC explores the parameter space of a given model that is being fit to a data set. It finds the areas of the parameter space that have a high probability, and thus allows an estimate of the parameter values and, importantly, their uncertainties. MCMC utilises Bayes' theorem:

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)},$$
(2.4)

where:

- P(A|B) is "the posterior:" the probability of A being true, given that B is true.
- P(B|A) is "the likelihood:" the probability of B being true, given that A is true.
- P(A) is "the prior:" the probability of A being true.
- P(B) is "the evidence:" the probability of B being true.

The MCMC sampler creates a chain: a set of values for the parameters are chosen, then there is a random step from these values to create a new set of parameters. Bayes' theorem is calculated for these sets of parameters, and then a comparison is made by taking the ratio of the posteriors, R. Whether or not the new parameters are accepted is based on a set of rules, often the Metropolis-Hastings algorithm (Metropolis et al., 1953; Hastings, 1970). In this, we accept the new parameters if $R \geq 1$, and then the chain is continued by taking a new random step and repeating the process. If R < 1, then the new parameters are only accepted as the next step in the chain with a probability of R; if they are not accepted, the new set of parameters are ignored and the old set of parameters are repeated as the next step in the chain. In both cases, a new random step is then taken and the process repeated.

The chain can take some time to start exploring the best areas of the parameter space, and so a number of steps are often discarded to ensure that the chains have converged when parameters are estimated. This is called "burn-in," and the number of steps to discard can be determined by visually assessing the chains to see where they converge. After burn-in, the number of steps taken is usually on the order of thousands. The samples are used to estimate the parameters and uncertainties, and for a Gaussian sample distribution, this is commonly done by taking the best-fit of the parameter as the median samples, and the 1σ uncertainty region as the 16th and 84th percentiles.

For my MCMC exploration, I use the Python implementation EMCEE (Foreman-Mackey et al., 2013).

2.2 Sample of Hot Jupiters

As stated in Section 1.2, in this study I define a hot Jupiter as an exoplanet with mass between 0.1 and 13 M_J 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, I have compiled a sample of confirmed transiting hot Jupiters taken from the NASA Exoplanet Archive. To ensure I have a sample free from any biases, I 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 K^2 (Howell et al., 2014), where only pre-selected stars were monitored. However, it does include the vast majority of hot Jupiter discoveries, as 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 the a synthetic galaxy population such as Besançon. I 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 and Fischer, 2015), which I did not wish to unintentionally bias the sample. Finally, I also exclude a small number of host stars with visual magnitudes of 9 or brighter. as for such systems I could not generate a large enough field star distribution from the Besancon Galaxy model.

My final sample consisted of 217 hot Jupiters, each with a corresponding host star. I present the properties of these hot Jupiters and their host stars in Figure 2.2 (left and right respectively), with parameters taken from the SWEET-Cat catalogue (Santos et al., 2013).

I adopt [Fe/H] as the measure of metallicity for this study (see Section 1.4), as it allows me to easily compile a homogeneous set of metalliticities for my host stars, and it means I can easily compare my 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. 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, I circumvent this issue. Other parameters for the host stars were taken from SWEET-Cat where available, otherwise they were taken from the NASA Exoplanet Archive. Parameters for the planets were also taken from the latter.



Figure 2.2: Properties of the 217 transiting hot Jupiters in my sample. Left: the hot Jupiter sample, displaying the mass and period selection criteria of 0.1 to 13 M_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 blue 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.

2.3 Besançon Simulation of Field Stars

In order to determine if there is a correlation between the occurrence of hot Jupiters and host star metallicity, I 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 my sample of hot Jupiter host stars was drawn. To make this simulation, I 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).

I performed the default Besançon Catalogue simulation without kinematics, using the Johnson-Cousins Photometric system. I created a population of simulated stars for each individual hot Jupiter host star, with a range of galactic latitude and longitude within 10 \deg^2 of the hot Jupiter host star. The simulated population was restricted to stars with a visual magnitude with $\delta V_{\text{mag}} = 1$ of the hot Jupiter host star. I further restricted the population to dwarf stars, which removed distant giants for which transit surveys are not sensitive to finding hot Jupiters around. Finally, I restricted the population to the mass range of the host star sample, from 0.52 to $1.6 M_{\odot}$, in order to remove very high mass stars, which again transit surveys are 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 my 217 hot Jupiter host stars, I selected 50 stars from the corresponding simulated stellar populations which were closest in visual magnitude value to the hot Jupiter host star. Thus my final set of simulated stellar populations comprised of 10850 stars in total.

In order to examine whether our simulated stellar populations accurately represent my sample of hot Jupiter hot stars, I make a comparison of the stellar mass distributions of each - see Figure 2.3. 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 me confidence that the simulated Besançon population does represent the stellar population from which the hot Jupiter host stars are drawn.



Figure 2.3: A comparison of the mass distribution of the host stars belonging to the hot Jupiter sample (blue), and the field stars simulated by the Besançon galaxy model (red). The field star sample has been cut to only include masses within the range of the host stars (0.52 to 1.6 M_{\odot}), and to only include 50 field stars of the closest visual magnitude to each host star. The masses from the model stars are in good agreement with the hot Jupiter host star masses.

2.4 Analysing the Planet-Metallicity Correlation

In the seminal work on the planet-metallicity correlation of Valenti and Fischer (2005), it was shown that the probability of a finding a giant planet rises sharply as a function of the metallicity of the star. Valenti and Fischer (2005) utilises a power law of the functional form

$$f([Fe/H]) \propto 10^{\beta[Fe/H]}$$
 (2.5)

to relate f, the fraction of stars with giant planets, to metallicity ([Fe/H]), where β is the index of the power law. I adopt this same formalism in quantifying the planet-metallicity correlation for hot Jupiters from my sample. I note that unlike Valenti and Fischer (2005) and many subsequent surveys, my study is not sensitive to probing the absolute occurrence rates of giant planets. Since I am simulating the stars from which our hot Jupiter hosts stars are drawn, I cannot determine the absolute occurrence rate of hot Jupiters. Instead, I solely probe the dependence of hot Jupiter occurrence on metallicity.

As discussed in Section 2.2, is it widely known that different analysis methods used to derive metallicity from optical spectra can introduce significant offsets in measured metallicity (Torres et al., 2012; Petigura et al., 2018). This issue is equally



Figure 2.4: Fig. 5 of Valenti and Fischer (2005), where they used a sample of 1040 FGK stars from an RV survey. The percentage of stars with planets increases with metallicity, and this is fit with the power law given in Equation 2.5.

true when comparing the metallicities of my hot Jupiter hosts from SWEET-Cat (Santos et al., 2013) to the metallicities of my simulated population of stars from the Besançon Galaxy Model (Robin et al., 2003). In order to address this issue, I need to allow for an offset between the SWEET-Cat metallicities and the Besançon metallicities. I do this by adding a offset term, c, to Equation 2.5 as follows:

$$f([Fe/H]) \propto 10^{\beta([Fe/H]+c)}.$$
(2.6)

Since I have a large sample of hot Jupiter hosts, and the offset is a linear shift between the SWEET-Cat and Besançon metallicities, I can simply fit for c and β simultaneously in an MCMC when comparing the populations of hot Jupiter hosts to the simulated field stars.

In order to fit our data with Equation 2.6, we go through a several step process, described below:

- 1. We are first required to weight each field star individually by Equation 2.6. We do this by substituting the parameter [Fe/H] with each field star's metallicity (using a fixed value for β and +c).
- 2. This gives an individual probability for each field star, and the metallicity of each field star is added to a new population a number of times proportional to this probability. This new population is then compared to our host star population by a KS test, giving a single statistic and p-value.

3. Steps (i) and (ii) are repeated as we explore the parameter space of β and +c 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 new population from step (ii) is more similar to the host star population, and thus that the values for β and +c are a better fit.

After a preliminary search over the $\{\beta, c\}$ parameter space, uniform priors were placed on both β and c, but they were restricted to the ranges $0 \le \beta \le 1.8$ and $0 \le c \le 0.2$. This process was run for 5000 steps after an initial 500 that were discarded as burn-in. The results are set out in Chapter 3.

Chapter 3

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 stars from which they were drawn. Figure 3.1 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 both the peak and shape of the 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 [Fe/H] = -0.115 ± 0.003 dex, while the hot Jupiter host stars is $[Fe/H] = 0.100 \pm 0.012$ dex, where the error is given as the standard error of the mean. This gives a significant metallicity difference of 0.215. A KS test comparing the distributions gives a statistic of 0.35 and a p-value of 1.47×10^{-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 3.2 shows the corner plot of the samples drawn in the MCMC exploration of the $\{\beta, c\}$ parameter space described in Section 2.4. From these samples, we estimate values for β and c of $0.71^{+0.56}_{-0.034}$ and $0.104^{+0.026}_{-0.033}$ respectively. These were estimated using the 16th, 50th, and 84th percentiles.

In Fig. 3.1 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 2.6 with our best fit β 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 β and c gives a statistic of 0.062 and a p-value

of 0.383. This shows that this distribution and the hot Jupiter host star distribution are indistinguishable.



Figure 3.1: Metallicity distributions for field stars simulated with the Besançon model (red), and hot Jupiter host stars from our sample with metallicities taken from SWEET-Cat (blue). A weighted sample distribution is also displayed (black outline), which corresponds to weighting the simulated field stars by applying Equation 2.6 (using the specific values of β and c estimated by the MCMC), as if they all hosted hot Jupiters.

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Figure 3.2: Corner plot displaying a 2D contour plot and 1D histograms of the samples drawn during the MCMC exploration of the parameter space. The solid orange lines show the median values, and the dashed orange lines show the lower and upper uncertainties using the 16th and 84th percentiles. The histogram titles display the median and $\pm 1\sigma$ uncertainties for each parameter. This plot was made using the CORNER.PY code (Foreman-Mackey, 2016).

Chapter 4

Discussion

My 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, I compare this to previous studies, examine any potential biases in my statistic sample, and discuss the implications of my results in terms of the formation and migration of hot Jupiters.

4.0.1 Comparisons with previous studies

Valenti and 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 drawn from a combination of the Keck M Dwarf Survey, the original SPOCS catalogue, and the SPOCS IV catalogue. They found a value of $\beta = 1.2 \pm 0.2$, which is slightly higher but fully consistent with my 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 β value of 2.3 ± 0.4 . Interestingly, this result is in good agreement with the Fischer and Valenti (2005) result, but not with the result of Johnson et al. (2010), or with my result.

While all of the above results are from radial velocity surveys, there have also been previous attempts to calculate β from transit surveys, in particular from the *Kepler* survey (Borucki et al., 2010). Guo et al. (2017) and Petigura et al. (2018) both evaluate β 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

Table 4.1. p value	ioni past merature.	•
Reference	Stellar Sample	eta
Valenti and Fischer (2005)	1040 FGK stars	2.0
	(RV survey)	
Johnson et al. (2010)	1194 AFGKM stars	1.2 ± 0.2
	(RV survey)	
Schlaufman (2014)	620 FGK stars	2.3 ± 0.4
	(RV survey)	
Guo et al. (2017)	13 Kepler hot	2.1 ± 0.7
	Jupiter hosts	
Petigura et al. (2018)	14 Kepler hot	$3.4^{+0.9}_{-0.8}$
	Jupiter hosts	0.0
This work	217 hot Jupiter	$0.71^{+0.56}_{-0.34}$
	hosts	0101

Table 4.1: β values from past literature.

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 my sample), means that these results need to be approached with some caution.

My 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. I summarise my result and the previous results in Table 4.1.

My β value is lower than all previously published results in Table 4.1. I am within 1σ of the result of Johnson et al. (2010); however, if I accounted for the mass dependency in my calculation as they have, I would expect our value for β to decrease further (though not significantly so, as the stellar masses in my sample have a range of only ~ $1M_{\odot}$). I am 2.32 and 2.31σ from Valenti and 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, I am 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.

4.0.2 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. 3.2, and is relatively small in comparison to the overall spread of metallicities (c.f. Fig. 3.1). The metallicity offset does correlate with β (see Fig. 3.2), which results in a relatively large and slightly asymmetric uncertainty on β .

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 my value of β , 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. I 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.

4.0.3 Hot Jupiter Formation and Migration

Examining the presence of the planet-metallicity correlation for hot Jupiters can provide evidence towards determining the mechanisms behind their formation and/or 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 disc 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 disc-driven migration and interactions with planetary companions when the hot Jupiter is misaligned with the stellar rotation axis (e.g. Dawson and 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 the 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 ~ 10 M_{\oplus} to ~ 4 M_J, 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.

My 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 my value for β 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 my result does not indicate an comparative increase in the metallicity of hot Jupiter systems.

Chapter 5

Conclusion

I 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 TrES, with metallicities taken from SWEET-Cat. I 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. I use the formalism of Valenti and Fischer (2005) (Equation 2.5) and find $\beta = 0.71^{+0.56}_{-0.34}$. This result is lower, but consistent to within uncertainties, to β values derived from radial velocity surveys that probe much longer period giant planets. I 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 of giant planets with 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 conjugation with a more complete and consistent survey of stellar metallicities.

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