**GIANT PLANETS ORBITING METAL-RICH STARS SHOW SIGNATURES OF PLANET–PLANET INTERACTIONS**

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**ABSTRACT**

Gas giants orbiting interior to the ice line are thought to have been displaced from their formation locations by processes that remain debated. Here we uncover several new metallicity trends, which together may indicate that two competing mechanisms deliver close-in giant planets: gentle disk migration, operating in environments with a range of metallicities, and violent planet–planet gravitational interactions, primarily triggered in metal-rich systems in which multiple giant planets can form. First, we show with 99.1% confidence that giant planets with semimajor axes between 0.1 and 1 AU orbiting metal-poor stars ([Fe/H] < 0) are confined to lower eccentricities than those orbiting metal-rich stars. Second, we show with 93.3% confidence that eccentric proto-hot Jupiters undergoing tidal circularization primarily orbit metal-rich stars. Finally, we show that only metal-rich stars host a pile-up of hot Jupiters, helping account for the lack of such a pile-up in the overall *Kepler* sample. Migration caused by stellar perturbers (e.g., stellar Kozai) is unlikely to account for the trends. These trends further motivate follow-up theoretical work addressing which hot Jupiter migration theories can also produce the observed population of eccentric giant planets between 0.1 and 1 AU.

**Key word:** planets and satellites: dynamical evolution and stability

**Online-only material:** color figures

1. INTRODUCTION

Approximately 1% of stars host hot Jupiters, ousted from their birthplaces to short-period orbits (Wright et al. 2012) via mechanisms that remain debated. Proposed theories fall into two classes: smooth disk migration (e.g., Goldreich & Tremaine 1980) and migration via gravitational perturbations, either by stars (e.g., stellar binary Kozai; Wu & Murray 2003) or sibling planets (including planetary Kozai, e.g., Naoz et al. 2011; scattering, e.g., Rasio & Ford 1996; and secular chaos, e.g., Wu & Lithwick 2011). (See Dawson et al. 2013, hereafter DMJ13, for additional references.) We consider the latter class as also encompassing gravitational perturbations preceded by disk migration (e.g., Guillochon et al. 2011).

Migration processes must not only produce hot Jupiters—heavily studied, extensively observed gas giants orbiting within 0.1 AU of their host stars—but also populate the region from 0.1 to 1 AU, interior to both the ice line and the observed pile-up of giant planets at 1 AU. This region is outside the reach of tidal damping forces exerted by the host star but interior to both the ice line and the observed pile-up of giant planets at 1 AU, one of which likely indicates where large, rocky cores can grow and accrete. We call this semimajor axis range the “Valley,” because it roughly corresponds to the “Period Valley” (e.g., Jones et al. 2003), the observed dip in the giant planet orbital period ($P$) distribution from roughly 10 < $P$ < 100 days. The Valley houses gas giants both on highly eccentric and nearly circular orbits. Gas disk migration is unlikely to excite large eccentricities (e.g., Dunhill et al. 2013), whereas dynamical interactions are unlikely to produce a substantial population of circular orbits. Therefore, this eccentricity distribution may point toward intermixing between two different migration mechanisms, one gentle and one violent. Another orbital feature—the bimodal distribution of spin–orbit alignments among hot Jupiters—is sometimes interpreted as evidence for two migration mechanisms (Fabrycky & Winn 2009; Morton & Johnson 2011; Naoz et al. 2012). However, it may result from stellar torques on the protoplanetary disk (Batygin 2012), gravity waves that misalign the star’s spin axis (Rogers et al. 2012), or two regimes for tidal realignment (Winn et al. 2010; Albrecht et al. 2012). Because tides are negligible in the Valley (except at the most extreme periastron, e.g., HD-80606-b, HD-17156-b), we can interpret trends more easily. Excited inclinations and eccentricities cannot have been erased by tidal damping.

If two common mechanisms indeed deliver close-in giant planets, physical properties of the protoplanetary environment may determine which is triggered. A decade ago, Santos et al. (2001, 2004) discovered that giant planets more commonly orbit metal-rich stars, supporting the core accretion formation theory. Independent and follow-up studies confirmed this trend for giant planets (e.g., Fischer & Valenti 2005; Sozzetti et al. 2009; Johnson et al. 2010; Sousa et al. 2011; Mortier et al. 2012) but not small planets (Ribas & Miralda-Escudé 2007; Buchhave et al. 2012). Neither the Santos et al. (2004) nor the Fischer & Valenti (2005) samples exhibited correlations between stellar metallicity and planetary period or eccentricity, but now the radial-velocity (RV) sample has quadrupled. It is time to revisit the planet–metallicity correlation, but now to gain insight into the dynamical evolution of planetary systems following planet formation.

Another motivation is the puzzlingly low occurrence rate of hot Jupiters in the *Kepler* versus RV sample (Youdin 2011; Howard et al. 2012; Wright et al. 2012). *Kepler* targets have systematically lower metallicities than RV targets. We will show that differences in the planetary period distribution—not just the overall occurrence rate—between metal-rich and metal-poor stars may account for the discrepancy.

We uncover new stellar metallicity trends in the eccentricities of giant Valley planets (Section 2), eccentricities of giant planets tidally circularizing (Section 3), and giant planet period...
distribution (Section 4). These correlations point toward planet–planet interactions as one of two mechanisms for delivering close-in gas giants (Section 5).

2. ECCENTRIC VALLEY PLANETS ORBIT METAL-RICH STARS

Valley gas giants are unlikely to have formed in situ (Rafikov 2006) and exhibit a range of eccentricities \(e\) (Figure 1). Here we consider giant planets discovered by radial-velocity surveys with \(m \sin i > 0.1 \, M_{\text{Jup}}\) (queried from the Exoplanet Orbit Database\(^1\) (EOD) on 1 March 2013; Wright et al. 2011). We restrict the sample to FGK stars \((0.4 < M_\star < 1.4 \, M_\odot)\).

Under the two migration mechanisms hypothesis, Valley planets on nearly circular orbits moved in smoothly through the gaseous protoplanetary disk, whereas those on eccentric orbits were displaced through multi-body interactions. In Figure 1, we emphasize planets with large eccentricities by plotting \(1 - e^2\). This quantity is related to the specific orbital angular momentum, \(h = \sqrt{a(1 - e^2)}\), an important parameter for dynamical interactions. This scale also minimizes eccentricity bias. For example, as a result of noise and eccentricity bias, a planet truly on a circular orbit could have a measured \(e \sim 0.1\). However, on this scale, \(e = 0.1\) would be nearly indistinguishable from \(e = 0\).

We divide the sample into planets orbiting metal-rich stars ([Fe/H] > 0; blue circles) versus metal-poor stars ([Fe/H] < 0; red squares). Only the metal-rich stars host Valley planets with large eccentricities. The eccentricities of these 61 planets extend up to 0.93. In contrast, the 17 Valley planets orbiting metal-poor stars are confined to low eccentricities \((e \leq 0.43)\). Overall, 28% of Valley planets orbiting metal-rich stars have eccentricities exceeding that of the most eccentric one orbiting a metal-poor star.

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\(^1\) Five planets fulfilling our selection criteria have eccentricities fixed at 0 in the EOD fits. We perform Monte Carlo Markov Chain fits to the RVs of 14-And-b \((e = 0.026^{+0.038}_{-0.019})\), HD-81688-b \((e = 0.031^{+0.021}_{-0.020})\), and Xi-Aql-b \((e = 0.26 \pm 0.04)\) using Sato et al.’s (2008) data; adopt Johnson et al.’s (2011) \(e = 0.03 < 0.28\) for HD-90663-b; and remove HD-104067-b because the RVs are unavailable.

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We assess the statistical significance of the low eccentricities of Valley planets orbiting metal-poor stars. We perform a Kolmogorov–Smirnov (K-S) test on the null hypothesis that the eccentricities of the metal-rich and metal-poor sample are drawn from the same distribution. We reject the null hypothesis with 96.9% confidence. Finally the probability that the maximum eccentricity of the 17 planets is less than or equal to the observed \(e = 0.43\) is the ratio of combinations:

\[
\frac{\binom{61}{17} \text{ Valley } e \leq 0.43}{\binom{78}{17} \text{ Valley } [\text{Fe/H}] < 0} = 0.86\% 
\]

The results are insensitive to the exact metallicity cut and significant at 95% confidence or higher for any cut located between \(-0.15\) and 0.03 dex. Therefore, with 99.14% confidence, we reject the hypothesis that the confinement to low eccentricities of the planets orbiting metal-poor stars results from chance. Although the exact statistical significance is somewhat sensitive to the definition of the Valley, which defines the sample size, it is evident in Figure 1 that the trend occurs throughout the Valley, and the significance of the results is 95% or higher for cuts from \(0.6 < a < 1.16\, \text{AU}\). The significance is 99.86% without the stellar cuts and 97.8% with an additional cut of \(\log g > 4\) to remove evolved stars.

As suggested by Johansen et al. (2012) in the context of the mutual inclinations of Kepler multi-planet systems, one might expect a threshold metallicity to trigger instability. Decreasing planets’ semimajor axes \((a)\) via gravitational perturbations requires interactions between at least two (and probably more) closely spaced giant planets. It may be that only metal-rich protoplanetary environments can form such systems.\(^2\) In contrast,

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\(^2\) RV systems containing multiple known giant planets do appear to have systematically higher metallicities than those containing one, but the statistical significance is marginal. We note that planets may be scattered to distances beyond current RV detection or ejected, so systems with only one known giant planet perhaps originally had more.

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Figure 1. Left: Valley (gray region) giant planets orbiting metal-rich stars ([Fe/H] > 0; blue circles) have a range of eccentricities; those orbiting metal-poor stars ([Fe/H] < 0; red squares) are confined to low eccentricities. Small symbols represent stars with \(\log g < 4\). For reference, above the dashed line (a tidal circularization track ending at 0.1 AU) planets are unlikely to experience significant tidal circularization. We plot the quantity \(1 - e^2\) to emphasize high-eccentricity planets. Right: eccentricity distributions of Valley planets orbiting metal-rich (blue solid) and metal-poor (red dashed) stars. The bold distributions omit stars with \(\log g < 4\). (A color version of this figure is available in the online journal.)
planets on circular orbits would have arrived via disk migration, which can occur regardless of metallicity.

We note that beyond 1 AU, the metal-rich and metal-poor samples have similar eccentricity distributions. Planets with \( a > 1 \) AU have not necessarily changed their semimajor axes: they may have formed where we observe them. These planets on eccentric orbits near their formation location may have exchanged angular momentum with another planet or star without requiring the abundance of closely packed giant planets necessary to drastically alter \( a \).

3. PROTO-HOT JUPITERS ORBIT METAL-RICH STARS

We turn to planets experiencing significant tidal dissipation, detected\(^3\) by non-Kepler transit surveys (Figure 2) and followed up with RV measurements. We use the stellar and planetary cuts described in Section 1 (except for XO-3-b, see below). Socrates et al. (2012) and DMJ13 used this sample to calculate the abundance of moderately eccentric proto-hot Jupiters. Advantageously for this sample, transit surveys are less inclined to target metal-rich stars, yielding planets orbiting metal-poor stars for comparison. To be consistent with Socrates et al. (2012) and DMJ13 and to avoid eccentricity bias, we classify planets with \( e > 0.2 \) as eccentric.

The striped region contains planets undergoing tidal circularization along tracks of constant angular momentum (see Socrates et al. 2012; DMJ13) to final orbital periods \( P_{\text{final}} \) between 2.8 and 10 days. (The traditional boundary for hot Jupiters is 10 days, and 2.8 days is the limit above which we still see eccentric giant planets. Those with \( P_{\text{final}} < 2.8 \) days have much faster tidal circularization rates.) Most observed eccentric planets orbit metal-rich stars (blue circles). We suggest that only giant planets forming in metal-rich systems with multiple giant planets are likely to be scattered onto eccentric orbits that bring them close enough to the star to undergo tidal circularization (e.g., Ford & Rasio 2006).

The probability of randomly selecting eight planets orbiting stars with \([\text{Fe/H}] > 0\) and one planet (i.e. XO-3-b) orbiting a star with \([\text{Fe/H}] < -0.18\) is the ratio of combinations:

\[
\frac{\binom{38}{8} \times 14 + \binom{38}{9}}{\binom{59}{9}} = 6.7\%
\]

where, among the 59 stars in the \( P_{\text{final}} \) range, 38 have \([\text{Fe/H}] > 0\) and 14 have \(-0.18 \leq [\text{Fe/H}] < 0\). XO-3 has \( M_* = 1.41 M_\odot \), just above our stellar mass cut; the high mass of the star (corresponding to a more massive disk and more metals to form giant planets) may account for the presence of a proto-hot Jupiter despite the star’s low metallicity. Without this star, the statistical significance is 98.3%. We also perform a K-S (A-D) test, rejecting with 95.5% (92.1%) confidence the null hypothesis that the host star metallicities of planets in the striped region with \( e > 0.2 \) are drawn from the same distribution as those with \( e < 0.2 \).

4. THE SHORT-PERIOD PILE-UP IS A FEATURE OF METAL-RICH STARS

Howard et al. (2012) found a surprisingly low Kepler hot Jupiter occurrence rate \((f_{\text{HJ,Kepler}})\)—the expected number of giant planets per star with \( P < 10 \) days—compared to RV surveys \((f_{\text{HJ,RV}})\), a trend confirmed by Wright et al. (2012) and Fressin et al. (2013); all suggested that the systematically lower metallicities of Kepler host stars may contribute to the discrepancy. In Figure 3, we compare the period distribution of transiting giant planet candidates detected by the Kepler survey (Burke et al. 2013; see also Borucki et al. 2011 and Batalha et al. 2013)—applying a radius cut of \( 8 < R_{\text{planet}} < 20 R_{\text{earth}} \)—to that expected from the RV sample\(^4\), using a normalization factor of 38:14:9 for \([\text{Fe/H}] > 0\), \([\text{Fe/H}] < 0\), and \([\text{Fe/H}] = 0\), respectively.

\(^{3}\) Some planets have \( e \) fixed at 0 in EOD fits. We remove those with poorly constrained eccentricities: CoRoT-7-b, HAT-P-9-b, OGLE-TR-10-b, OGLE-TR-111-b, TrES-1-b, TrES-4-b, WASP-13-b, WASP-39-b, WASP-58-b, XO-1-b, XO-5-b. We include planets whose eccentricities are constrained to be small \((e < 0.2)\), by our fits (CoRoT-13-b, CoRoT-17-b, WASP-16-b) or the literature (CoRoT-7-b, HAT-P-1-b, HAT-P-4-b, HAT-P-8-h, HAT-P-12-h, HAT-P-27-h, HAT-P-39-b, OGLE-TR-211-b, KELT-2-Ab, WASP-7, WASP-11-b, WASP-15-b, WASP-21-b, WASP-25-b, WASP-31-b, WASP-35-b, WASP-37-b, WASP-41-b, WASP-42-b, WASP-47-b, WASP-61-b, WASP-62-b, WASP-63-b, WASP-67-b). See the EOD for each planet’s orbital reference.

\(^{4}\) The RV sample is not uniform; we plot it for qualitative comparison. The expected distribution derived from the period distribution reported by Cumming et al. (2008) appears similar. We therefore interpret the short-period pile-up as real, not due to preferential detection. For the quantitative calculations in this section, we use the uniform Fischer & Valenti (2005) sample.
constant $C_{\text{norm}}$ (defined below). The RV sample includes only planets discovered by RV surveys, not transit surveys. For both samples, we follow DMJ13 and impose cuts of stellar temperature $4500 < T < 6500$ K and surface gravity $\log g > 4$ to restrict the sample to well-characterized Kepler host stars (Brown et al. 2011). The two distributions appear consistent beyond 10 days but differ strikingly at short orbital periods: the Kepler period distribution lacks a short-period pile-up (in fact, the absolute Kepler giant planet occurrence declines toward short orbital periods, as modeled by Youdin 2011 and Howard et al. 2012).

Although KIC metallicity estimates are known to be uncertain (Brown et al. 2011), we can roughly divide the Kepler sample into metal-rich ([Fe/H] $\geq 0$) and metal-poor ([Fe/H] < 0). In Figure 4, we compare the period distributions for Kepler giant planets orbiting metal-rich versus metal-poor stars. When we limit the sample to [Fe/H] $\geq 0$ (row 2), we recover the missing short-period pile-up, which the metal-poor sample (row 3) lacks. Performing a K-S test, we reject with 99.95% confidence the hypothesis that the metal-rich sample and metal-poor sample are drawn from the same distribution. The results are insensitive to the exact metallicity cut.

We compare the Kepler metal-rich(poor) sample to the RV metal-rich(poor) sample in Figure 5. In Figures 3 and 5, we compare the observed number of transiting Kepler giant planets (red striped) to the number expected (black dashed) based on the RV sample,

$$N_{\text{RV,trans}} = C_{\text{norm}} N_{\text{RV}} f_{\text{HJ,Kepler}}$$

where $N_{\text{RV}}$ is the observed number of RV planets per bin and $f_{\text{HJ,trans}}(P)$ is the transit probability. We set the normalization constant, $C_{\text{norm}}$, using the values (computed below) of $f_{\text{HJ,Kepler}}$ and $f_{\text{HJ,RV}}$:

$$C_{\text{norm}} = \frac{f_{\text{HJ,RV}} \sum_{P=0}^{10 \text{days}} N_{\text{trans,Kepler}}(P) / \text{prob}_{\text{trans}}(P)}{f_{\text{HJ,Kepler}} \sum_{P=0}^{10 \text{days}} N_{\text{RV}}(P)}.$$
We obtain $f_{\text{HJ, RV}} = 1.03^{+0.34}_{-0.32}\%$ for giant planets with $P < 10$ days (in agreement with Wright et al. 2012), $1.74^{+0.67}_{-0.54}\%$ for those orbiting stars with $[\text{Fe/H}] \geq 0$, and $0.07^{+0.23}_{-0.06}\%$ for $[\text{Fe/H}] < 0$. With no metallicity cut, $f_{\text{HJ, Kepler}}$ is inconsistent with $f_{\text{HJ, RV}}$ at the 2.0$\sigma$ level.

In the metal-rich comparison (Figure 5, left), we see greater consistency between the Kepler and RV distribution than in the full sample (Figure 3). The metal-rich Kepler sample exhibits a short-period pile-up; the discrepancy between $f_{\text{HJ, Kepler}}$ versus $f_{\text{HJ, RV}}$ is now only 1.0$\sigma$, with the greatest discrepancy in the 3–5 day bin. This improvement motivates a detailed follow-up analysis, including a more precise estimate of $f_{\text{HJ, RV}}$ using the latest RV target lists. If follow-up studies find a significant discrepancy between the metal-rich Kepler and RV samples, it could be due to the KIC metallicity estimates. Using spectroscopic metallicity measurements by Buchhave et al. (2012), we find that high metallicities do correspond linearly to high spectroscopic metallicities (with a scatter of about 0.2 dex about a best-fit line with slope 0.3), but the spectroscopic metallicities have a systematic offset corresponding to 0.1 dex at KIC $[\text{Fe/H}] = 0$, as also noted by Brown et al. (2011). However, we attribute the systematic offset to factors targeted for spectroscopic follow-up that are bright, main-sequence stars in our solar neighborhood and thus have systematically higher metallicities; in contrast, the KIC metallicities were computed assuming a low-metallicity prior, due to the Kepler targets being above the galactic plane. The planetary radius cut may also contribute to the discrepancy. The $8R_{\text{earth}}$ cut for the Kepler sample corresponds to the RV cut of $m \sin i = 0.1M_{\text{Jup}}$ for planets made of pure hydrogen at a low effective temperature (e.g., Seager et al. 2007). However, close-in, low-mass planets may be inflated to $>8R_{\text{earth}}$ and may have a different period distribution, contaminating the sample. In the metal-poor comparison (Figure 5, right), the Kepler and RV distributions do not appear inconsistent, but it is difficult to judge given the very small sample of RV-detected planets orbiting metal-poor stars.

5. CONCLUSION

We found three ways in which the properties of hot Jupiters and Valley giants depend on host star metallicity.

1. Gas giants with $a < 1$ AU orbiting metal-rich stars have a range of eccentricities, whereas those orbiting metal-poor stars are restricted to lower eccentricities.
2. Metal-rich stars host most eccentric proto-hot Jupiters undergoing tidal circularization.
3. The pile-up of short-period giant planets, missing in the Kepler sample, is a feature of metal-rich stars and is largely recovered for giants orbiting metal-rich Kepler host stars.

Hot Jupiters and Valley giants are both thought to have been displaced from their birthplaces. Therefore, these metallicity trends can be understood if smooth disk migration and planet–planet scattering both contribute to the early evolution of systems of giant planets. We expect that disk migration could occur in any system, but only systems packed with giant planets—which most easily form around metal-rich stars—can scatter giant planets inward to large eccentricities (trend 1). Some of these eccentric orbits are shrunk and circularized by tides (trend 2), creating a pile-up of short-period giants (trend 3). Moreover, these trends support planet–planet interactions (e.g.,
scattering, secular chaos, or Kozai) as the dynamical migration mechanism for delivering close-in giant planets, rather than stellar Kozai. This is consistent with previous work by DMJ13 arguing that stellar Kozai does not produce most hot Jupiters, based on the lack of super-eccentric proto-hot Jupiters. We would not expect planet–planet scattering to typically result in nearby companions to hot Jupiters, which have been ruled out in the Kepler sample by Steffen et al. (2012). (See also Latham et al. 2011.)

One possible challenge for our interpretation is the lack of apparent correlation between spin–orbit misalignment and metallicity. However, spin–orbit misalignments are not necessarily caused by dynamical perturbations, and their interpretation is complicated because measurements have primarily been performed for close-in planets subject to tidal realignment. We recommend spin–orbit alignment measurements, via spectroscopy (McLaughlin 1924; Rossiter 1924; Queloz et al. 2000) or photometry (Nutzman et al. 2011; Sanchis-Ojeda et al. 2011), of Kepler candidates in the Valley, which are typically too distant to be tidally realigned.

To support or rule out the interpretation that these metallicity trends are signatures of planet–planet interactions, we further recommend (1) theoretical assessments of whether planet–planet interaction mechanisms designed to account for hot Jupiters can simultaneously produce the observed population of eccentric Valley planets, and (2) more sophisticated assessments of the trends we report here, using the target lists of recent RV surveys and, as undertaken by Fressin et al. (2013), a careful treatment of Kepler false-positives and detection thresholds.

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