Constraining Planetary Migration Mechanisms in Systems of Giant Planets

Rebekah I. Dawson, Ruth A. Murray-Clay and John Asher Johnson

Harvard-Smithsonian Center for Astrophysics
60 Garden St, MS-10, Cambridge, MA 02138

Abstract. It was once widely believed that planets formed peacefully in situ in their proto-planetary disks and subsequently remain in place. Instead, growing evidence suggests that many giant planets undergo dynamical rearrangement that results in planets migrating inward in the disk, far from their birthplaces. However, it remains debated whether this migration is caused by smooth planet-disk interactions or violent multi-body interactions. Both classes of model can produce Jupiter-mass planets orbiting within 0.1 AU of their host stars, also known as hot Jupiters. In the latter class of model, another planet or star in the system perturbs the Jupiter onto a highly eccentric orbit, which tidal dissipation subsequently shrinks and circularizes during close passages to the star. We assess the prevalence of smooth vs. violent migration through two studies. First, motivated by the predictions of Socrates *et al.* (2012), we search for super-eccentric hot Jupiter progenitors by using the "photoeccentric effect" to measure the eccentricities of Kepler giant planet candidates from their transit light curves. We find a significant lack of super- eccentric proto-hot Jupiters compared to the number expected, allowing us to place an upper limit on the fraction of hot Jupiters created by stellar binaries. Second, if both planet-disk and multi-body interactions commonly cause giant planet migration, physical properties of the proto-planetary environment may determine which is triggered. We identify three trends in which giant planets orbiting metal rich stars show signatures of planet-planet interactions: (1) gas giants orbiting within 1 AU of 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; and (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. These two studies suggest that both disk migration and planet-planet interactions may be widespread, with the latter occurring primarily in metal-rich planetary systems where multiple giant planets can form. Funded by NSF-GRFP DGE-1144152.

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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). We assess the prevalence of these two classes through two studies. In Section 2, we search for super-eccentric hot Jupiter progenitors in the *Kepler* sample, expected if hot Jupiters migrated via gravitational perturbations. If both planet-disk and multi-body interactions commonly cause giant planet migration, physical properties of the proto-planetary environment may determine which is triggered. In Section 3, we identify three trends in which giant planets orbiting metal rich stars show signatures of planet-planet interactions.

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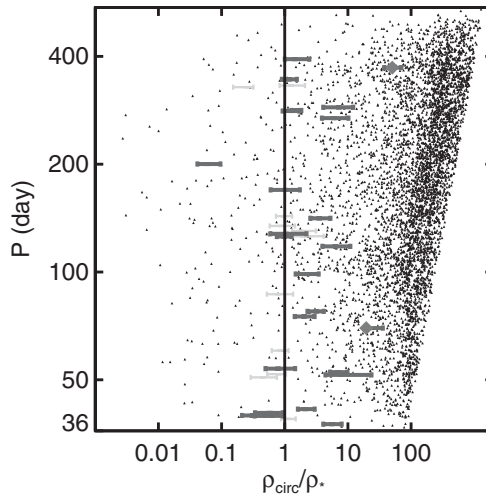
Figure 1. Expected 2D posterior for orbital period P vs. $\rho_{\rm circ}/\rho_\star$. The values we measured for *Kepler* giant planet candidates (Batalha *et al.* 2013) are overplotted. Thin, light bars: candidates with companions in their systems. Thick, dark bars: candidates with no known companions. We do not see the expected half a dozen candidates in the region of high-probability density. Diamonds: KOI-1474.01 (bottom), KOI-211.01 (top).

2. A paucity of super-eccentric Jupiters

One or more companions can create a hot Jupiter by perturbing a cold Jupiter onto an eccentric orbit, which tidal forces shrink and circularize during close passages to the star. Socrates *et al.* (2012, S12 hereafter) predicted that if this "high-eccentricity migration" (HEM) is the primary channel for producing hot Jupiters, the *Kepler* candidate collection should harbor a population of super-eccentric Jupiter-sized planets that are in the midst of tidal circularization. We have been using what we term the "photoeccentric effect" to measure individual eccentricities of Jupiter-sized planets from their transit light curves (Dawson & Johnson 2012). Dawson *et al.* (2012) identified KOI-1474.01 as a transiting planet candidate with a long orbital period (69.7 days), a large eccentricity ($e = 0.81 \pm 0.10$), and transit timing variations caused by a massive outer companion. However, uncertainty in the candidate's eccentricity made it ambiguous whether KOI-1474.01 is one of the proto-hot Jupiters predicted by S12 or, alternatively, a failed-hot Jupiter beyond the reach of tidal circularization over its host star's lifetime.

Here we examine the entire sample of *Kepler* Jupiters to assess whether the planets expected from HEM are present. We perform a Monte Carlo simulation to predict the signature in the transit light curve observable $\rho_{\rm circ}/\rho_\star$ expected from the super-eccentric proto-hot Jupiters. Following the procedure described in Dawson *et al.* (2013), we generate a two-dimensional (2D) probability distribution in $(P, \rho_{\rm circ}/\rho_\star)$ (Figure 1, black dots), where P is the orbital period, $\rho_\star$ the bulk stellar density, $\rho_\star = M_\star/(\frac{4}{3}\pi R_\star^3)$, and $\rho_{\rm circ}$ is the stellar density measured from the light curve under the assumption of a circular orbit. Next, we fit stellar evolution models to the host stars and transit models to the light curves of *Kepler* giant planet candidates (see Dawson *et al.* 2012, Dawson *et al.* 2013). Finally, we combine the $\rho_{\rm circ}$ and $\rho_\star$ posteriors into a posterior of $\rho_{\rm circ}/\rho_\star$ for each candidate, marginalized over all other parameters. None of the candidates fall in the high-probability area of the prediction. Applying the statistical procedure described in Dawson *et al.* (2013), we find that, with 95.8% confidence, we detected too few super-eccentric proto-hot Jupiters to be consistent with the prediction. We place a
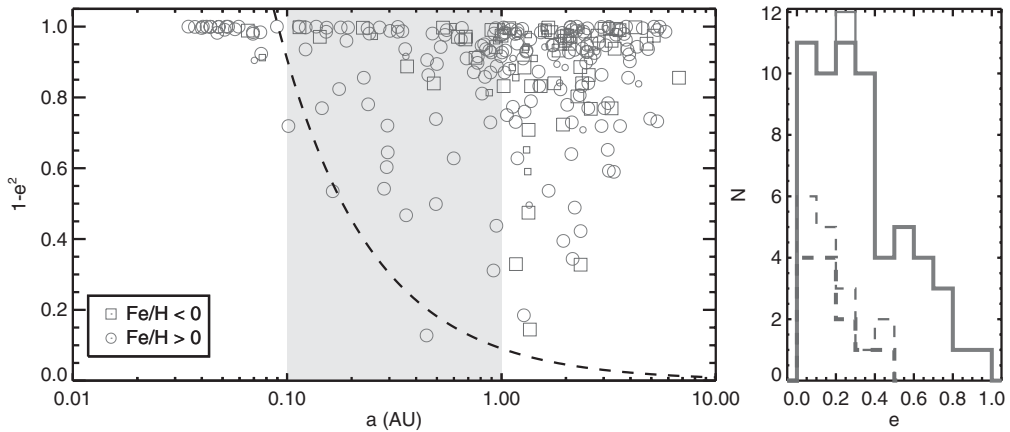
Figure 2. Left: "Valley" (gray region) giant planets orbiting metal-rich stars ([Fe/H]$\geqslant$0, circles) have a range of eccentricities; those orbiting metal-poor stars ([Fe/H]<0, squares) are confined to low eccentricities. Small symbols represent stars with $\log g < 4$. For reference, above the 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 (solid) and metal-poor (dashed) stars. The bold distributions omit stars with $\log g < 4$.

two-sigma upper limit of 33% on the fraction of moderately-eccentric proto-hot Jupiters ($0.2 < e < 0.6$) that began beyond the ice line with $e \rightarrow 1$. Since this is the only pathway open to hot Jupiters produced by stellar binary Kozai oscillations, the upper limit is also on the fraction of hot Jupiters created by stellar binaries.

3. Giant planets orbiting metal-rich stars show signatures of planet-planet interactions

We find three ways in which the properties of hot Jupiters and Valley giants depend on host star metallicity (see Dawson & Murray-Clay 2013 for a quantative, statistical assessment):

(a) 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 (Figure 2; see also Taylor 2012).

(b) Metal-rich stars host most eccentric proto-hot Jupiters undergoing tidal circularization (Dawson & Murray-Clay 2013, Figure 2).

(c) 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 (Figure 3; Dawson & Murray-Clay 2013, Figure 5) .

Hot Jupiters and Valley giants (those with semi-major axes beyond 0.1 AU but interior to the pile-up at 1 AU) 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 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 tides shrink and circularize (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
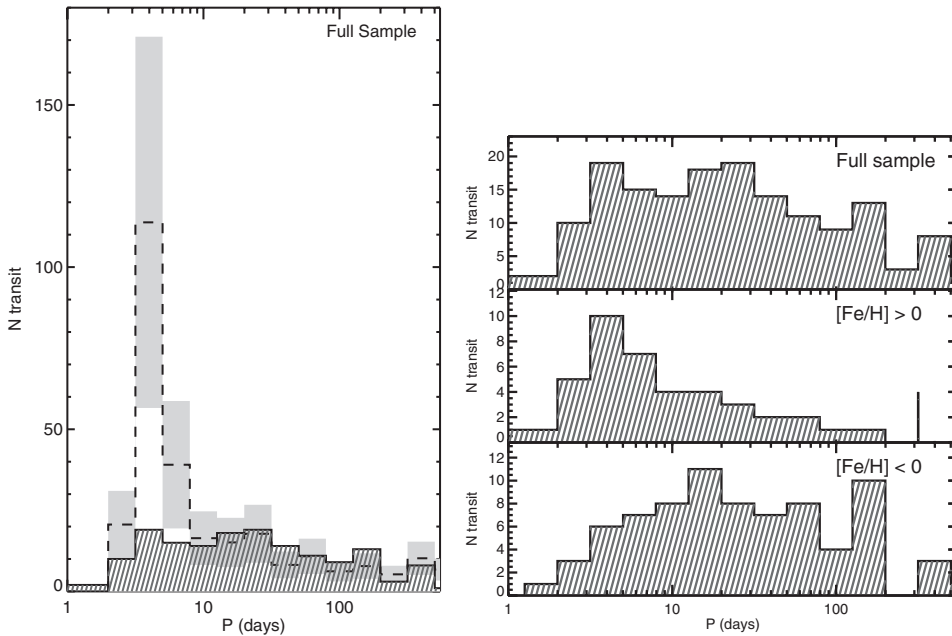
Figure 3. Left: Striped striped: number of transiting giant planets detected by *Kepler.* Black dashed: expected number based on the RV-discovered (i.e. excluding planets discovered by transit surveys) sample. The gray error bars are from uncertainties in C_{norm}, not the Poisson uncertainties of each individual bin. The two distributions are consistent at long periods, but the *Kepler* sample lacks a short period pile-up. Right: Number of transiting giant planets observed by *Kepler* without a stellar metallically cut (top), with [Fe/H]$\geqslant$0 (middle), and with [Fe/H]<0 (bottom). In the metal-rich sample (middle), we recover the shape of the short-period pile-up seen in the RV sample (black-dashed line, Figure 2). In contrast, the metal-poor sample (bottom) is depleted in short-period giants.

migration mechanism for delivering close-in giant planets, rather than stellar Kozai. This is consistent with the conclusion of Section 2 that stellar Kozai does not produce most hot Jupiters, based on the lack of super-eccentric proto-hot Jupiters.

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Discussion

RAFIKOV: What are the current prospects for directly constraining the non-smooth migration scenario by detecting 3rd body in the system?

DAWSON: Heather Knutson's group is searching for long period companions to hot Jupiters revealed by radial-velocity trends and adaptive-optics imaging. Monte Carlo simulations, folding in observational bias and detection limits, could be used to infer whether the detected companions are consistent with being the third body perturbers and even potentially distinguish between different non-smooth migration scenarios, though it may be challenging to do the latter analysis robustly. Failed hot Jupiters, like KOI-1474, are also important for constraining migration scenarios, and some of them have detected transit-timing variations due to perturbing companions, the population of which may also help distinguish among migration scenarios.

WIKTOROWICZ: Don't you only get a lower limit to eccentricity from Kepler transit durations?

DAWSON: There is indeed a lower limit, but we actually get a tighter constraint than just a lower limit by marginalizing over all periapse orientations. Note that we need to constrain both the duration and the slope of the light curve. If planet is moving more quickly than if it were on a circular orbit, a wide range of periapse orientations produce a light curve similar to that if the planet were transiting at periapse, so the inferred eccentricity probability distribution is mostly concentrated close to the minimum eccentricity.