PLANETS ON THE EDGE

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Received 2014 March 5; accepted 2014 April 11; published 2014 May 2

Abstract
Hot Jupiters formed through circularization of high-eccentricity orbits should be found at orbital separations \( a \) exceeding twice that of their Roche limit \( a_R \). Nevertheless, about a dozen giant planets have now been found well within this limit \( (a_R < a < 2a_R) \), with one coming as close as 1.2 \( a_R \). In this Letter, we show that orbital decay (starting beyond 2 \( a_R \)) driven by tidal dissipation in the star can naturally explain these objects. For a few systems (WASP-4 and 19), this explanation requires the linear reduction in convective tidal dissipation proposed originally by Zahn and verified by recent numerical simulations, but rules out the quadratic prescription proposed by Goldreich & Nicholson. Additionally, we find that WASP-19-like systems could potentially provide direct empirical constraints on tidal dissipation, as we could soon be able to measure their orbital decay through high precision transit timing measurements.

Key words: planet–star interactions – planets and satellites: gaseous planets – planetary systems – stars: evolution – stars: general

Online-only material: color figures

1. INTRODUCTION

Almost 200 of the known transiting exoplanets are giant planets with orbital periods less than 10 days. These so-called hot Jupiters were most likely formed farther out at several AUs, but the debate continues on whether their tight orbits are the result of quasi-circular disk migration or high-eccentricity migration. The first scenario involves slow orbital decay in a protoplanetary disk (Goldreich & Tremaine 1980; Lin et al. 1996; Ward 1997; Murray et al. 1998), while the second involves tidal circularization of an orbit made extremely eccentric by gravitational interaction with companion stars, or between several planets (Rasio & Ford 1996; Wu & Murray 2003; Fabrycky & Tremaine 2007; Nagasawa et al. 2008; Wu & Lithwick 2011; Naoz et al. 2011; Plavchan & Bilinski 2013). In this Letter, we focus on the hot Jupiters close to their Roche limits and show that they provide an important test for giant planet formation theories. In particular, this population provides constraints on the efficiency of convective damping of equilibrium tides (Zahn 1966, 1989; Goldreich & Nicholson 1977; see also Sasselov 2003).

In the disk-migration scenario, gas giants should be naturally found distributed in orbital separations, all the way down to the Roche limit \( a_R \). Instead, in any high-eccentricity migration scenario, Ford & Rasio (2006) pointed out that tidal circularization would lead to an inner edge at 2 \( a_R \). While the great majority of systems are indeed observed to lie beyond 2 \( a_R \) (e.g., Matsumura et al. 2010 and Figure 1 here), several hot Jupiters have now been discovered inside this limit. In a recent paper (Valsecchi & Rasio 2014, hereafter VR14), we targeted giant planets in misaligned systems (where the stellar spin and orbital angular momentum are misaligned on the plane of the sky) and we showed that their properties could be naturally explained through high-eccentricity migration. Hot Jupiters can then be formed with a broad distribution of misalignments \( \lambda \) and in orbits with a high eccentricity, which is quickly dissipated by planetary tides (Jackson et al. 2008; Matsumura et al. 2010). Subsequently, stellar tides, magnetic braking, and stellar evolution lead to the observed distribution of \( \lambda \) found around stars of different temperatures (Winn et al. 2010; Albrecht et al. 2012). Here we consider the known hot Jupiters close to tidal disruption and investigate the possibility that these same physical mechanisms are responsible for bringing them inward from beyond 2 \( a_R \). As the tides exerted on the star by the planet are expected to be too weak to keep up with the spin-down driven by magnetic braking (Barker & Ogilvie 2009), the resulting dissipation in the slowly rotating host star drives further orbital decay. With future measurements of the shift in transit times (e.g., Sasselov 2003; Birkby et al. 2014), the orbital decay rate could be determined. This, in turn, would provide important constraints for both tidal dissipation and hot Jupiter formation theories. In contrast to previous studies on these objects (e.g., Sasselov 2003; Gillon et al. 2014; Birkby et al. 2014), we use detailed stellar models and compute the orbital evolution of hot Jupiters by integrating the equations describing the coupled evolution of the orbital elements and stellar spin (VR14).

This Letter is organized as follows. We describe our hot Jupiter sample in Section 2 and explain how we model each host star in Section 3. In Section 4 we summarize the physical mechanisms included in our orbital evolution calculations and we emphasize the tidal prescriptions considered. We present our results in Section 5 and conclude in Section 6.

In what follows \( M_*, R_*, T_{\text{eff}}, \text{Fe/H} \) (or \( Z \)), \( \lambda \) (\( \Theta_\lambda \)), and \( v_{\text{rot}} \sin i_* \) indicate the stellar mass, radius, effective temperature, metallicity, sky-projected (true) misalignment, and rotational velocity, respectively. The angles \( \lambda \) and \( \Theta_\lambda \) are related via \( \cos \Theta_\lambda = \sin i_* \cos \lambda \sin i_\phi + \cos i_* \cos i_\phi \) (Fabrycky & Winn 2009). The angle between the stellar spin axis (the orbital angular momentum) and the line of sight is \( i_\phi \) (\( i_\phi \)). The planetary mass (radius) is \( M_\text{pl} \) (\( R_\text{pl} \)). The stellar spin frequency and planetary orbital frequency are \( \Omega_\star \) and \( \Omega_\text{orb} \), respectively. The orbital period (separation) is \( P_\text{orb} \) (\( a \)).

2. HOT JUPITERS WITHIN 2 \( a_R \)

The systems were queried from the NASA Exoplanet Archive on 2014 February 20. In Figure 1 we show \( M_\text{pl}/M_* \) as a function
of $a/a_R$ for the full sample of exoplanets currently known (left) and for the systems considered here (right). We adopt Paczyński’s (1971) approximation $a_R = R_p / (0.462 q^{1/3})$, where $q = M_p / M_*$ $\ll 1$. The vertical dotted line marks the $a/a_R = 2$ limit, beyond which lie the great majority of systems. Here we focus on the hot Jupiters inside this limit where no additional bodies have been found (marked in gray, as such bodies could perturb the orbital evolution of the inner planet). We summarize their properties in Table 1.

### 3. STELLAR MODELS

The host star models are shown in Figure 2 and are chosen from the grid of evolutionary tracks described in VR14 (computed with MESA; Paxton et al. 2011, 2013) as follows. To be within the 1σ uncertainties in $M_*$ and Fe/H, while still close to the mean observed values, OGLE-TR-56, WASP-4, 19, and 48’s models are chosen randomly among those whose $M_*$ $(\text{Fe/H})$ are within 0.04 $M_\odot$ (0.05) from the observed mean values at some point during the stellar evolution. The same procedure is applied to CoRoT-1 and WASP-103, but requiring the limit on $M_*$ $(\text{Fe/H})$ to be 0.03 $M_\odot$ (0.05). The age of Wasp-52 varies by several Gyr, depending on its properties. Hébrard et al. (2013) report a lower limit of 0.5 Gyr from lithium abundance and quote a gyrochronological age of 0.4+1.4-1 Gyr derived from the observed $v_{\text{rot}} \sin i_*$ (Hébrard et al. 2013 and references therein). However, $i_*$ is not known. To see some degree of orbital evolution, we take the model that reaches the oldest age within the 1σ uncertainties in $M_*$ and Fe/H. This model spans a range $\approx 1.5$–7 Gyr. Finally, WASP-78 is not in VR14’s catalogue, and we evolve a star with the observed mean $M_*$ and $Z$. The observed $R_*$ and $T_{\text{eff}}$ can be matched only within $2 \sigma$. The agreement could
be improved by varying some of the physics entering the stellar modeling (e.g., the mixing length parameter, which is usually varied between 1 and 2 in the literature, see Paxton et al. 2011, 2013). However, we choose not to introduce additional free parameters and therefore apply the same physical assumptions to all systems.

4. ORBITAL EVOLUTION

The procedure and assumptions adopted in our calculations are explained in detail in VR14. Here we outline the main points for clarity and present the new tidal prescriptions considered. We study CoRoT-1 b, OGLE-TR-56 b, WASP-4, 19, 48, 52, and 103 b’s evolutionary past, by scanning the initial (at the stellar Zero Age Main Sequence (ZAMS)) parameter space made 1σ b’s evolutionary past, by scanning the initial (at the stellar Zero Age Main Sequence (ZAMS)) parameter space made 1σ around the initial parameters (hereafter the Zahn prescription, respectively). However, we choose not to introduce additional free parameters and therefore apply the same physical assumptions to all systems.

For stellar wind mass loss and magnetic braking we proceed as in VR14, introducing the parameter γMB, which controls the strength of angular momentum loss via magnetic braking. For tides, we use the weak-friction approximation when there is no information about misalignment (and we then take Θ∗ = 0). Instead, for systems where the misalignment has been constrained, we include the effect of inertial wave dissipation (IWD) following Lai (2012), and consider a variety of initial Θ∗. When accounting for weak-friction tides alone, we consider both sub- and super-synchronous initial configurations (Ω∗, < Ω∗, and Ω∗ > Ω∗, respectively) and vary Ω∗/ΩH between 0 and 100 in steps of 0.2. We halt the calculation if the star is spinning faster than break-up. Instead, when accounting for IWD, we consider initial Ω∗/ΩH values only up to 0.9, according to the validity of the Lai (2012) prescription. Furthermore, we consider different values for the efficiency of IWD by varying the tidal quality factor Q1/2.

Thus far, we followed VR14, apart from enforcing the validity of Lai’s (2012) recipe for tides (initial Ω∗/ΩH < 1). Now we go one step further and vary the weak-friction tides prescription following Sasselov (2003). In VR14 we included the effects of both convective damping of the equilibrium tide and radiative damping of the dynamical tide and showed that, in the weak-friction regime, the former always dominates for typical hot Jupiter systems. For convective dissipation, we followed the mixing-length theory of convection and assumed that the oscillatory tidal distortion is dissipated by turbulent (eddy) viscosity. For high tidal forcing frequencies, the efficiency of angular momentum transport by the largest eddies is inhibited, and the exact form of this reduction is still under debate. Defining the reduction factor as

$$f_{\text{conv}} = \min \left[ 1, \left( \frac{P_{\text{tid}}}{2 \tau_{\text{conv}}} \right)^s \right],$$

where $P_{\text{tid}}$ and $\tau_{\text{conv}}$ are the tidal forcing period and the convective turnover timescale (VR14 and references therein), two commonly used prescriptions are the linear one ($s = 1$) proposed by Zahn (1966, 1989) and supported by Penet et al.’s (2007) recent numerical simulations, and the quadratic one ($s = 2$) proposed by Goldreich & Nicholson (1977). Here we follow Sasselov (2003) and consider both $s = 1$ and $s = 2$ (hereafter the Zahn and GN prescription, respectively).

At each time step during the calculation we check that the planet is within its Roche lobe (Paczyński 1971). We stop the evolution when the model’s $M_*, R_*$, $T_{\text{eff}}$, $v_\text{rot} \sin i_*$, and Θ∗ (if constrained) are within 1σ ($2\sigma$ in $R_*$ and $T_{\text{eff}}$, for WASP-78) from the observed values and $P_{\text{orb}}$ crosses the present value (Table 1).

5. RESULTS

Our numerical results are summarized in Table 2. The parameter $T_{\text{shift}}$ is the transit arrival time shift, which we computed following Section 7.2 of Birkby et al. (2014) and our $\dot{a}$ values. Here we follow Birkby et al. (2014) and assume 10 yr of observations with a timing accuracy of 5 s (Gillon et al. 2009). However, note that orbital periods are routinely measured to less than 1 s with multiple observations (J. Steffen 2014, private communication). In Table 2, we therefore list the full range of $T_{\text{shift}}$ values computed. We perform a first scan in initial orbital periods ($P_{\text{orb}, \text{ini}}$) with a coarse resolution, which we then increase during a second scan, if needed. In Table 2 we list the results with limited precision, just to give a sense for the possible initial orbital configurations.

Half of the systems considered are easily explained: CoRoT-1, OGLE-TR-56, WASP-48, and 103, according to our detailed modeling, started their orbital evolution from beyond 2 $a_0$, independent of the tidal prescription adopted (Zahn or GN). On the other hand, the evolutionary picture differs for WASP-4 and 19, where only the Zahn prescription is consistent with...
system cannot be explained by the scenario. Furthermore, within our initial parameter space, this of its age could provide constraints on the more likely migration prescription only if

\[ a_{\text{in}} > 2a_R. \]

While \( T_{\text{shift}} \) for WASP-4 is lower than the 5 s limit considered by Birkby et al. (2014), it is 5–8 times this limit for WASP-19, according to \( Zahn \). If detected, it could provide important constraints on tidal dissipation theory. Interestingly, WASP-19-like systems could also be used to constraint the efficiency of IWD. In fact, within the range of \( Q_{10} \) values considered and given the resolution of our initial parameter space, this system can be explained by the \( Zahn (GN) \) prescription only if \( Q_{10} < 10^{10} (Q_{10} > 10^7) \). Finally, WASP-52 and 78 are consistent with \( a_{\text{in}} > 2a_R \) only for the longest \( P_{\text{orb,in}} \) considered. For WASP-52, a more precise determination of its age could provide constraints on the more likely migration scenario. Furthermore, within our initial parameter space, this system cannot be explained by the \( GN \) prescription. This is due to the upper limit imposed on the initial \( \Omega_o/\Omega_s \). For WASP-78 the efficiency of tides is never reduced and both tidal prescriptions predict the same evolutionary picture. This system could still be used to constrain hot Jupiter formation theories from measurements of \( T_{\text{shift}} \).

The ages constrained with our modeling (Table 2) agree with those reported in the literature (when available) for most systems. WASP-48’s age is uncertain and, even though we list the one derived by the lack of lithium and Ca H+K, we note that the rotation rate supports an age of 0.6±0.2 Gyr. Alternatively, isochrones analysis yields an age of 3.0±0.3 Gyr (Enoch et al. 2011 and references therein).

The parameter \( \gamma_{MB} \) is generically set to 0.1 and 1 for F- and G-dwarfs (Barker & Ogilvie 2009; Matsumura et al. 2010), respectively. We find solutions for nearly any of the \( \gamma_{MB} \) values considered for OGLE-TR-56, WASP-4, and 52, with both tidal prescriptions, and for WASP-4, and 103 with the \( Zahn \) prescription. Furthermore, the \( \gamma_{MB} \) range that explains WASP-78 (\( \gamma_{MB} < 0.3 \)) and 103 (\( \gamma_{MB} < 1 \) and 0.2 for \( Zahn \) and \( GN \), respectively) encloses the value 0.1 generally adopted for F-dwarfs. Instead, CoRoT-1, WASP-4, and 19, with G-dwarfs, all have \( \gamma_{MB} < 1 \). According to \( Zahn (GN) \), we find \( \gamma_{MB} \leq 0.1 \) (0.2) both for CoRoT-1 and WASP-19. On the other hand, for WASP-4, the \( GN \) prescription allows \( \gamma_{MB} \leq 0.2 \) (0.9) for \( Q_{10} = 10^8 \) (\( \geq 10^7 \)). This discrepancy and the fact that the \( GN \) prescription cannot explain WASP-52 is due to the upper limit on the initial \( \Omega_o/\Omega_s \) considered here (0.9), as the Lai (2012) recipe for tides is strictly valid for sub-synchronous systems. In this regime, IWD affects only \( \Omega_o \), while it might affect \( a \) when \( \Omega_o > \Omega_s \) (see VR14), but we do not account for this possibility. Since we find evolutionary solutions for initial \( \Omega_o/\Omega_s \) values up to 0.9, super-synchronous configurations would likely yield more solutions and higher \( \gamma_{MB} \) values. However, a different prescription for the evolution of \( a \) should then be adopted or a detailed study of the significance of IWD compared to the other physical mechanisms should be performed (VR14).

In Figure 3 we show, as an example, the detailed evolution of a WASP-4-like system according to \( Zahn (GN) \) in black (blue). This is an interesting system since only with the \( Zahn \) prescription could its orbit have begun beyond \( 2a_R \).

For both tidal prescriptions, the evolution of \( a \) is driven by convective damping of the equilibrium tide, which drives to orbital decay (top panels). The evolution of \( \Omega_o \) is driven overall by magnetic braking if the \( GN \) prescription is adopted. This causes the star to spin-down. Instead, according to \( Zahn \), magnetic braking dominates for the first \( \approx 2 \) Gyr and the remaining evolution is driven by weak-friction tides. The latter contributes to spin-down until the system is \( \approx 5 \) Gyr old and \( \Theta_s > 90^\circ \). After \( \Theta_s \) has crossed 90° (marked by a sudden peak in the timescales) the derivative describing the tidal evolution of the stellar spin in the weak-friction regime changes sign, and tides tend to synchronize \( \Omega_o \) with \( \Omega_s \). Finally, the evolution of the misalignment is driven by IWD with the \( GN \) prescription and by both weak-friction tides and IWD with the \( Zahn \) prescription. These effects cause the misalignment to decrease to the currently observed value.

| Name   | \( a_{\text{in}} \) (a\(_R\)) | \( T_{\text{shift}} \) (Gyr) | \( P_{\text{orb,in}} \) (days) | \( T_{\text{shift}} \) (s) | \( t_{\text{mod}} \) (Gyr) |
|--------|-------------------------------|-------------------------------|-----------------------------|-----------------------------|-----------------------------|
| C-1    | 1.7                           | 2.7–3.1 (2.0–2.7)             | 3.2–3.8 (2.0–3.2)           | 2.2–3.7 (0.3–0.8)           | 4.3–5.1                     |
| O-56   | 1.7                           | 2.8–3.5 (2.2–2.7)             | 2.7–3.5 (1.7–2.3)           | 3.2–3.8 (0.3–0.8)           | 4.3–5.1                     |
| W-4    | 1.7                           | 2.7–2.9 (1.9–1.9)             | 2.3–3.6 (1.5–1.5)           | 2.2–3.7 (0.3–0.8)           | 4.3–5.1                     |
| W-19   | 1.2                           | 2.9–3.2 (2.8–2.7)             | 3.3–3.6 (1.5–1.5)           | 2.2–3.7 (0.3–0.8)           | 4.3–5.1                     |
| W-48   | 1.8                           | 3.1–3.3 (2.4–3.0)             | 3.3–3.7 (2.2–3.1)           | 64 – 116 (5.2 – 7.9)        | 2.8–3.4 (2.7–3.4)           |
| W-52   | 1.6                           | 3.3–3.6 (2.8–2.7)             | 3.2–3.8 (2.0–2.8)           | 1.7–2.1 (1.6–1.7)           | 4.3–5.4                     |
| W-78   | 1.8                           | 3.1–3.3 (2.4–3.0)             | 3.2–3.7 (2.2–3.1)           | 64 – 116 (5.2 – 7.9)        | 2.8–3.4 (2.7–3.4)           |

Notes. See Table 1 for system names. The parameter \( t_s \) is the stellar age, while \( T_{\text{shift}} \) is the transit arrival time shift (see text). The subscripts “in” and “pr” refer to the literature and our modeling, respectively. The subscripts “in” and “pr” refer to initial (at the ZAMS) and present values, respectively. For \( a_{\text{in}}, P_{\text{orb,in}}, T_{\text{shift}}, \) and \( t_{\text{mod}} \), we list outside of and in parentheses the parameters derived using the \( GN \) prescription for tides, respectively (Section 4). If there are no parentheses, the two numbers agree (e.g., in W-78 the efficiency of IWD is never reduced).

References. Following exoplanet.eu; (1) Sasselov 2003; (2) Enoch et al. 2011; (3) Smalley et al. 2012 and references therein; (4): Gillon et al. 2014; (5) Gillon et al. 2009; (6) Adams et al. 2011; (7) Hébrard et al. 2013.
6. CONCLUSION

We investigated tidal dissipation and giant planet formation theories, by focusing on hot Jupiters with orbits close to the Roche limit ($a_R$). In particular, we tested whether their properties are consistent with high-eccentricity migration—where the highly eccentric orbits of giant planets are tidally circularized, through tidal dissipation in the planet, to distances larger than $2a_R$, and later orbital decay is produced by tidal dissipation in the star. We studied CoRoT-1 b, OGLE-TR-56 b, WASP-48, 19, 48, 52, 78, and 103 b and computed the past evolution of their orbital separation, stellar spin, and misalignment (when observed), including the effects of stellar tides and wind mass loss, magnetic braking, and the evolution of the host star. For the reduction in the effectiveness of convective damping of the equilibrium tide when the forcing period is less than the turnover period of the largest eddies, we tested the linear and quadratic theory of Zahn (1966, 1989) and Goldreich & Nicholson (1977), respectively.

We found that CoRoT-1, OGLE-TR-56, WASP-48, and 103 are consistent with high-eccentricity migration, independent of the tidal prescription adopted. This same conclusion may hold for WASP-78, depending on its initial orbital configuration. This could be validated by future measurements of the transit arrival time shift ($T_{\text{shift}}$, e.g., Sasselov 2003; Birkby et al. 2014). Within the parameter space considered here, WASP-52 can only be explained by Zahn’s (1966, 1989) prescription. Furthermore, this system could be consistent with high-eccentricity migration, depending on its initial orbital configuration. While $T_{\text{shift}}$ for WASP-52 might be too small to detect, a more precise determination of its age could be used to distinguish between the different migration scenarios. Finally, WASP-4 and WASP-19 are consistent with high-eccentricity migration only according to Zahn’s (1966, 1989) prescription. For WASP-19 in particular, the fairly rapid orbital decay could lead to a significant $T_{\text{shift}}$ which, if detected, would provide an important confirmation of these ideas.

The three-dimensional numerical simulations by Penev et al. (2007) showed a reduction factor that closely matched the linear prescription by Zahn (1966, 1989). With this prescription, the results presented here show that all systems currently known close to their Roche limit are indeed consistent with a high-eccentricity migration scenario for the formation of hot Jupiters.

This work was supported by NASA Grant NNX12AI86G. We thank Jason Steffen for his constructive remarks and comments. This research has made use of the NASA Exoplanet Archive.

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