WARM JUPITERS NEED CLOSE “FRIENDS” FOR HIGH-ECCENTRICITY MIGRATION—A STRINGENT UPPER LIMIT ON THE PERTURBER’S SEPARATION

SUBO DONG1,2, BOAZ KATZ2,3,4, AND ARISTOTELE SOCRATES2,3

1 Kavli Institute for Astronomy and Astrophysics, Peking University, Yi He Yuan Road 5, Hai Dian District, Beijing 100871, China
2 Institute for Advanced Study, 1 Einstein Dr., Princeton, NJ 08540, USA

Received 2013 August 30; accepted 2013 December 3; published 2013 December 23

ABSTRACT

We propose a stringent observational test on the formation of warm Jupiters (gas-giant planets with 10 days ≤ P ≤ 100 days) by high-eccentricity (high-e) migration mechanisms. Unlike hot Jupiters, the majority of observed warm Jupiters have pericenter distances too large to allow efficient tidal dissipation to induce migration. To access the close pericenter required for migration during a Kozai–Lidov cycle, they must be accompanied by a strong enough perturber to overcome the precession caused by general relativity, placing a strong upper limit on the perturber’s separation. For a warm Jupiter at a ∼ 0.2 AU, a Jupiter-mass (solar-mass) perturber is required to be ≤3 AU (≤30 AU) and can be identified observationally. Among warm Jupiters detected by radial velocities (RVs), >50% (5 out of 9) have known Jovian companions satisfying this necessary condition for high-e migration. In contrast, ≤20% (3 out of 17) of the low-e (e ≤ 0.2) warm Jupiters have detected additional Jovian companions, suggesting that high-e migration with planetary perturbers may not be the dominant formation channel. Complete, long-term RV follow-ups of the warm-Jupiter population will allow a firm upper limit to be put on the fraction of these planets formed by high-e migration. Transiting warm Jupiters showing spin–orbit misalignments will be interesting to apply our test. If the misalignments are solely due to high-e migration as commonly suggested, we expect that the majority of warm Jupiters with low-e (e ≤ 0.2) are not misaligned, in contrast with low-e hot Jupiters.

Key word: planetary systems

Online-only material: color figures

1. INTRODUCTION

The origin of warm Jupiters (gas giants with period 10 days < P < 100 days) presents a similar puzzle to that of hot Jupiters (P ≤ 10 days)—neither population can form in situ according to popular theories of planet formation—yet much less attention has been paid to the former.

Rossiter–Mclaughlin measurements reveal that a considerable fraction of transiting hot Jupiters have orbits misaligned with host star spin axes (e.g., Winn et al. 2010; Trijau et al. 2010), which provide indirect support to high-eccentricity migration mechanisms (Rasio & Ford 1996; Wu & Murray 2003; Fabrycky & Tremaine 2007; Wu & Lithwick 2011; Socrates et al. 2012b). These high-e mechanisms involve the initial excitation of hot Jupiter progenitors at a few AU to very high eccentricity due to gravitational perturbations by additional objects in the system. The excitation is then followed by successive close pericenter passages (r_p ≤ 0.05 AU) that drain the orbital energy via tidal dissipation. The hot Jupiter progenitors eventually become hot Jupiters at a < 0.1 AU.

The majority of known warm Jupiters are sufficiently distant from their hosts (a_p = a(1 − e^2) > 0.1 AU) to forbid efficient tidal dissipation, due to the strong distance dependence of tidal effects. However, if the orbital eccentricity of a warm Jupiter is experiencing Kozai–Lidov oscillations due to an external perturber (Holman et al. 1997; Takeda & Rasio 2005), then it may be presently at the low-e stage in the cycle and over a secular timescale, reach an eccentricity high enough for tidal dissipation to cause significant migration (e.g., Wu & Lithwick 2011). A schematic illustration of such a high-e migration scenario is shown in Figure 1 (red solid line). Warm Jupiters detected by radial velocity (RV) are shown in dots in Figure 1 within the black dashed lines. We define Jovian planets to have minimum mass M_J > 0.3 M_Jup and set an upper limit in the semimajor axis of 0.5 AU for warm Jupiters. This upper bound is well below the theoretical “snow line” of in situ core-accretion formation at about 2.5–3 AU for solar-type stars (e.g., Kennedy & Kenyon 2008) and the observed “jump” in the a distribution of giant planets at ∼1 AU (e.g., Wright et al. 2009).

In planet–planet scattering, a Jupiter can migrate without tidal dissipation by a factor of ~2 if another Jupiter is ejected (Rasio & Ford 1996), and our upper bound in distance is set to disfavor such a process.

We discuss a stringent observational constraint on warm Jupiter formation via high-e migration—they must be accompanied by close, easily observable perturbers. These close perturbers are strong enough to overcome the precession caused by general relativity (GR) to reach close enough periapses for effective tidal dissipation within Kozai–Lidov cycles. In contrast, high-e migration for hot Jupiters is not subject to such a stringent constraint on perturbers. Hot Jupiter progenitors can be excited to close periapses at their initial, relatively large semimajor axes with distant perturbers, and throughout the subsequent migration, their periapses may keep close enough for tidal dissipation. Hot Jupiters formed by high-e migration can thus have distant perturbers that are difficult to detect.

2. PERTURBER CONSTRAINTS ON WARM-JUPITER HIGH-E MIGRATION

We derive below a lower limit on the perturber strength for warm-Jupiter in high-e migration due to tidal dissipation. We adopt a conservative criterion that tidal dissipation may
operate when a Jovian planet reaches \( a_\text{crit} = a(1 - e^2) < 0.1 \) AU. Observationally, the eccentricities of Jovian planets circularize at \( a_{\text{Jup}} \sim 0.06 \) AU (e.g., Socrates et al. 2012a). Given that tidal dissipation has a strong dependence on planet–star separation, it is safe to assume that tidal dissipation ceases to be efficient when \( a_\text{crit} > a_{\text{Jup}, \text{crit}} \approx 0.1 \) AU. We stress that the criterion presented below is a necessary but not an adequate condition for high-\( e \) migration. Without satisfying the criterion, the migration cannot occur, while fulfilling this requirement does not guarantee migration.

Consider a warm Jupiter with mass \( M_p \) at semimajor axis \( a \) and eccentricity \( e_0 \) orbiting a star with mass \( M \) accompanied by a perturber of mass \( M_{\text{per}} \) at \( a_{\text{per}} \) and \( e_{\text{per}} \). The criterion is to require the warm Jupiter to reach \( a(1 - e^2) < a_{\text{Jup}, \text{crit}} \approx 0.1 \) AU during Kozai–Lidov oscillation (see Figure 2 for an example). At a given \( a \), the amplitude of Kozai–Lidov oscillation in eccentricity is limited by sources of precession other than those induced by the perturber and is insensitive to tidal dissipation. At \( a_{\text{Jup}} \sim 0.1 \) AU, the precessions due to tides and the rotating bulge of the host are negligible compared to GR for typical hosts. Below we consider the Kozai–Lidov oscillation at the warm Jupiter’s current \( a \) due to the gravitational perturbation and GR precession. We ignore tidal dissipation and precession.

An analytical constraint is derived under the simplest assumptions: (1) quadrupole approximation in perturbing potential, (2) the warm Jupiter treated as test particle, (3) and the equation of motion is averaged over outer and inner orbits (“double-averaging”). We show below with numerical simulations that these are excellent approximations in deriving this constraint.

Under these approximations, the following is a constant (e.g., Fabrycky & Tremaine 2007):

\[
e^2(2 - 5 \sin^2 \omega \sin^2 \omega) + \frac{\epsilon_{\text{GR}}}{\sqrt{1 - e^2}} = \text{const},
\]

where

\[
\epsilon_{\text{GR}} = \frac{8GM^2\sin^3\omega}{c^3a^3M_{\text{per}}}
\]

\[
\approx 1.3 \left( \frac{M}{M_\odot} \right)^2 \left( \frac{a}{0.2 \text{AU}} \right)^{-4} \left( \frac{M_{\text{per}}}{M_\odot} \right)^{-1} \left( \frac{b_{\text{per}}}{3 \text{AU}} \right)^3
\]

\[
\approx 1.4 \left( \frac{M}{M_\odot} \right)^2 \left( \frac{a}{0.2 \text{AU}} \right)^{-4} \left( \frac{M_{\text{per}}}{M_{\text{Jup}}} \right)^{-1} \left( \frac{b_{\text{per}}}{3 \text{AU}} \right)^3
\]

represents the relative strength of GR compared to the perturber, \( i \) is the planet–perturber mutual inclination, \( \omega \) is the argument of pericenter, and \( b_{\text{per}} = a_{\text{per}}(1 - e_{\text{per}}^2)^{1/2} \) is the perturber’s semimajor axis.

From Equation (1), to reach an eccentricity \( e \) from \( e_0 \), the following criterion must be satisfied regardless of the values of \( i \) and \( \omega \):

\[
\epsilon_{\text{GR}} \left( \frac{1}{\sqrt{1 - e^2}} - \frac{1}{\sqrt{1 - e_0^2}} \right) < 2e_0^2 + 3e^2.
\]

We then put a lower limit on the “strength” of the perturber to reach \( a(1 - e^2) < a_{\text{Jup}, \text{crit}} \) (and an upper limit on the separation
The Astrophysical Journal Letters, 781:L5 (5pp), 2014 January 20

Dong, Katz, & Socrates

The blue lines show the analytical upper limit (Equation (4)) in the ratio of the perturber constraint of warm Jupiters for high-mass perturbers. The results are in excellent agreement with the analytical constraint given by Equation (4) for the appropriate eccentricity, \( e_0 = 0.3 \) (dashed blue lines), accurately traces the border of required perturbers for achieving the required eccentricity. Note that at the limit given in Equation (4), the strength of the octupole, \( \sim e_{\text{oct}} = a/\alpha_{\text{crit}}(1 - e_0^2)/(1 - e_{\text{per}}^2) \), is negligible compared to GR, \( \epsilon_{\text{GR}} \sim 1 \). While a small octupole can change the orbital inclination and lead to Kozai cycles with growing eccentricities, the eccentricity cannot surpass the limit Equation (4), which is the maximal value for all mutual orientations.

For the scenarios considered, the Kozai–Lidov timescale is much longer than the outer (and inner) orbital timescales, justifying the double averaging assumption. To illustrate this, the results of a direct three-body integration are compared to those of a double-averaging integration in Figure 2. The considered warm Jupiter is at \( a = 0.3 \) AU and \( e_0 = 0.3 \) and has a solar-mass perturber corresponding to the limit derived from Equation (4) with \( e_{\text{per}} = 0.5 \) and \( b_{\text{per}} = 68.8 \) AU. The initial inclination is at 90°. The results of two integrations are practically indistinguishable (black dashed: double-averaging; red solid: direct three-body), validating the double-averaging approximation. The approximation is even better for a Jupiter-mass perturber satisfying the same constraint. This is because it has a shorter period and a similar Kozai–Lidov timescale.

In the limit of \( a \gg a_{\text{crit}} \) and \( e_0 \to 0 \), the following useful approximation can be obtained using Equation (4):

\[
\frac{b_{\text{per}}}{a} < \left( \frac{8GM_\odot}{3e^2 a_\odot} \right)^{-1/3} \left( \frac{M_{\text{per}}}{M_{\text{per}}} \right)^{-1/3} \\
\times \left[ 2e_0^3 + 3(1 - a_{\text{crit}}/a) \right]^{1/3} \left( \frac{a}{a_{\text{crit}}} - \frac{1}{1 - e_0^2} \right)^{-1/3},
\]

(4)

Figure 3 shows the constraints on \( b_{\text{per}} \) for \( M_{\text{per}} = M_\odot \) and \( M_{\text{per}} = M_{\text{Jup}} \) in the upper and lower panels, respectively, derived from Equation (4) for \( a_{\text{crit}} = 0.1 \) AU. The blue lines from above to below are for \( e_0 = 0.5, 0.3, \) and 0.0, respectively (\( e_0 = 0.3 \) in dashed lines while others in solid lines).

Recently, it was realized that corrections due to various approximations above may lead to significant effects in several scenarios (e.g., Ford et al. 2000; Naoz et al. 2011; Katz et al. 2011b; Lithwick & Naoz 2011; Katz & Dong 2012).

We show that the analytic constraint given by Equation (4) are not affected by the inaccuracies of the adopted approximations using numerical integrations without these approximations. The effects of the quadrupole and test particle approximations are studied by performing 20,000 simulations (10,000 for \( M_{\text{per}} = M_\odot \) and 10,000 for \( M_{\text{per}} = M_{\text{Jup}} \)). These simulations employ the double averaged approximation but include the octupole term and are not restricted to the test particle approximation. The warm Jupiters have \( e_0 = 0.3 \) and \( a \) uniformly distributed (randomly) between 0.15 and 0.5 AU. The eccentricities of the outer perturbers are uniformly distributed within 0–0.5. The ratio \( b_{\text{per}}/a \) are uniformly distributed within 100–300 (10–30) for solar-mass (Jupiter-mass) perturbers. The orbital orientations of the outer and inner orbits are randomly distributed isotropically. All runs were integrated to 5 Gyr. The results are shown in Figure 3. The integrations in which the warm Jupiter reaches \( a(1 - e^2) < a_{\text{crit}} = 0.1 \) AU are plotted as red dots and others in black. The analytical constraint given by Equation (4) for the appropriate eccentricity, \( e_0 = 0.3 \) (dashed blue lines), accurately traces the border of required perturbers for achieving the required eccentricity.

\[
\frac{b_{\text{per}}}{a} < \left( \frac{8GM_\odot}{3e^2 a_\odot} \right)^{-1/3} \left( \frac{M_{\text{per}}}{M_{\text{per}}} \right)^{-1/3} \\
\times \left[ 2e_0^3 + 3(1 - a_{\text{crit}}/a) \right]^{1/3} \left( \frac{a}{a_{\text{crit}}} - \frac{1}{1 - e_0^2} \right)^{-1/3},
\]

(4)

We stress that this approximation should be used for order-of-magnitude estimates since it is only accurate in the limit \( e \to 0 \) and \( a \gg a_{\text{crit}} = 0.1 \) AU.

For warm Jupiters with \( a \sim 0.1–0.5 \) AU with Jovian-planet perturbers, this constraint leads to an upper limit in orbital separation of \( \sim 1.5–10 \) AU (period 2–30 yr). The RV semi-amplitude is \( \lesssim 10 \text{ m s}^{-1} \), accessible to available high-precision RV instruments. The perturbers at the high end in period range (\( \sim 20–30 \) yr) are more challenging since they may not have completed the full orbits yet during the monitoring projects. While for more massive perturbers, the upper limit in orbital separation implies much longer periods (\( P_{\text{per}} \propto M_{\text{per}}^{1/2} \)), they can generally be identified from the easily detectable RV linear trends.

\[
\frac{b_{\text{per}}}{a} \approx 17 \left( \frac{M_{\text{per}}}{M_\odot} \right)^{1/3} \left( \frac{M_{\text{per}}}{M_{\text{Jup}}} \right)^{-2/3} \left( \frac{a}{0.2 \text{ AU}} \right)^{1/6} \left( \frac{a_{\text{crit}}}{0.1 \text{ AU}} \right)^{1/6},
\]

(5)

See relevant discussion in “Maximal e and General Relativity (GR) precession” of Katz et al. (2011a).
Moreover, out of the five warm Jupiter systems with three or more planets (55 Cnc b, GJ 876 c, and HIP 57274 c), which are challenging to explain with high-$e$ migration. In contrast, for the five eccentric warm Jupiters at $e > 0.4$, there are no known additional planets in the system other than their Jovian perturbers, all of which are located further than 2 AU yet close enough to satisfy the constraint from Equation (4). This is indicative that the majority of low-$e$ warm Jupiters are unlikely due to high-$e$ migration induced by planet perturbers. It is worth noting that $M_p \sin i$ rather than $M_p$ is constrained from RV, so the above results are statistical. Note that the perturbers for all five eccentric warm Jupiters have larger $M_p \sin i$ than the inner planets, consistent with simple expectations from the planet–planet scattering scenario that less massive planets are easier to get excited into high-$e$ orbits.

We caution that the conclusions may be affected if the chance for detecting an outer perturber strongly depends on the eccentricity of the inner planet. The observing strategies in RV surveys can be complicated, especially for those involving multiple planets. For example, Wright et al. (2009) pointed out that a system was observed more frequently after a planet was found, so the detection of a massive planet would likely facilitate the discovery of smaller planets. A similar selection effect may make the detection of perturbers of eccentric warm Jupiters easier if their eccentricities attract particular attentions. A comprehensive sensitivity study would be helpful. Additionally, there are a number of possible modeling degeneracies that may masquerade a double low-$e$ planet system as an eccentric warm Jupiter (Rodigas & Hinz 2009; Anglada-Escudé et al. 2010). Systematic modeling efforts are possibly needed to evaluate such degeneracies. There might be other mechanisms that produce eccentric warm Jupiters associated with a perturber, including scattering followed by disk migration similar to Guillochon et al. (2011) and scattering of three planets with the third planet being ejected (C. Petrovich et al., in preparation).

High-precision RV surveys ($\lesssim 5 \text{ m s}^{-1}$) on thousands of stars have lasted for $\sim 15$ yr (e.g., Mayor et al. 2011; Wright et al. 2009; Wittenmyer et al. 2011). For a considerable fraction of their targets, they can detect Jupiters at $\lesssim 5$ AU with full orbits (though note that some discoveries from these surveys remain unpublished). Given our constraint on the axis ratio of $\sim 20$ for Jovian perturbers, this implies the present observational constraint on planet perturbers are likely relatively incomplete for warm Jupiters at $\gtrsim 0.3$ AU. For these systems, a thorough analysis of incomplete orbits and trends in RV is required.

Unlike close solar-type companions, low-mass stellar and brown dwarf companions are unlikely to be excluded from the RV samples to search for planets. The combined efforts of RV linear trends and high-contrast imaging will yield excellent constraints for such perturbers (e.g., Crepp et al. 2012).

Rossiter–McLaughlin effects for transiting planets are an important diagnostic for high-$e$ migration, to which the spin–orbit misalignments have been commonly attributed. No ground-based surveys have so far detected transiting warm Jupiters.
Note that the Kepler-30 system contains a warm Jupiter and the orbits of its three planets are shown to be aligned with the spin axis of the host (Sanchis-Ojeda et al. 2012). The three planets are in a compact orbit configuration, and they are unlikely to be formed by high-\(e\) migration.

\(a_f = a(1 - e^2) > a_{\text{crit}} = 0.1 \text{ AU}. \)

Yet it is interesting to note that, among the ground-based transiting planets with the longest period, possibly requiring eccentricity oscillations for tidal migration, several have known additional planet companions or have large RV linear trends (e.g., HAT-P-17b, Howard et al. 2012; WASP-8b, Queloz et al. 2010; KELT-6b, Collins et al. 2013). Future ground-based surveys or space-based surveys targeting bright stars are likely to discover warm Jupiters suitable for spin–orbit alignment measurements (note a possible transiting warm Jupiter candidate with a strong perturber identified by Dawson et al. 2012). They will be particularly interesting candidates subject to our proposed observational test on perturbers. If the spin–orbit misalignments are solely due to high-\(e\) migration, and given that the majority of low-\(e\) warm Jupiters do not seem to have strong enough perturbers for high-\(e\) migration, we expect that the majority of warm Jupiters with low-\(e\) (\(e \lesssim 0.2\)) will be found to be aligned with the spin axes of their hosts.

Finally, if the warm Jupiters are indeed migrating due to tidal dissipation at the high-\(e\) stage during Kozai–Lidov oscillations, they should be tidally powered and luminous enough to be detected by the future high-contrast imaging facilities such as those to be installed at the Thirty Meter Telescope, the Giant Magellan Telescope, and the European Extremely Large Telescope (Dong et al. 2013a). Similar high-\(e\) migration mechanisms have also been raised for the formation of close binary stars at \(P \lesssim 10\) days (Fabrycky & Tremaine 2007; Dong et al. 2013b), and the constraint we derive in this work can also be applied to test the formation of binaries at 10 days \(\lesssim P \lesssim 100\) days due to high-\(e\) mechanisms.

We thank Andy Gould, Scott Tremaine, and Cristobal Petrovich for discussions. We are grateful to the referee for a helpful report. S.D. was partly supported through a Ralph E. and Doris M. Hansmann Membership at the IAS and by NSF grant AST-0807444. B.K. is supported by NASA through the Einstein Postdoctoral Fellowship awarded by Chandra X-ray Center, which is operated by the Smithsonian Astrophysical Observatory for NASA under contract NAS8-03060. B.K. and A.S. acknowledge support from a John N. Bahcall Fellowship at the Institute for Advanced Study, Princeton. This research has made use of the Exoplanet Orbit Database and the Exoplanet Data Explorer at exoplanets.org.

REFERENCES

Anglada-Escudé, G., López-Morales, M., & Chambers, J. E. 2010, ApJ, 709, 168

Collins, K. A., Eastman, J. D., Beatty, T. G., et al. 2013, arXiv:1308.2296

Crepp, J. R., Johnson, J. A., Howard, A. W., et al. 2012, ApJ, 761, 39

Dawson, R. I., Johnson, J. A., Morton, T. D., et al. 2012, ApJ, 761, 163

Dong, S., Katz, B., & Socrates, A. 2013a, ApJL, 762, L26

Dong, S., Katz, B., & Socrates, A. 2013b, ApJL, 763, L2

Fabrycky, D., & Tremaine, S. 2007, ApJ, 669, 1298

Ford, E. B., Kozinsky, B., & Rasio, F. A. 2000, ApJ, 535, 385

Guillochon, J., Ramirez-Ruiz, E., & Lin, D. 2011, ApJ, 732, 74

Holman, M., Touma, J., & Tremaine, S. 1997, Natur, 386, 254

Howard, A. W., Bakos, G. A., Hartman, J., et al. 2012, ApJ, 749, 134

Katz, B., & Dong, S. 2012, arXiv:1211.4568

Katz, B., Dong, S., & Malhotra, R. 2011a, arXiv:1106.3340

Katz, B., Dong, S., & Malhotra, R. 2011b, PhRvL, 107, 181101

Kennedy, G. M., & Kenyon, S. J. 2008, ApJ, 673, 502

Lithwick, Y., & Naoz, S. 2011, ApJ, 742, 94

Mayor, M., Marmier, M., Lovis, C., et al. 2011, arXiv:1109.2497

Naoz, S., Farr, W. M., Lithwick, Y., Rasio, F. A., & Teyssandier, J. 2011, Natur, 473, 187

Queloz, D., Anderson, D. R., Collier Cameron, A., et al. 2010, A&A, 517, L1

Rasio, F. A., & Ford, E. B. 1996, Sci, 274, 954

Rodigas, T. J., & Hinz, P. M. 2009, ApJ, 702, 716

Sanchis-Ojeda, R., Fabrycky, D. C., Winn, J. N., et al. 2012, Natur, 487, 449

Socrates, A., Katz, B., & Dong, S. 2012a, arXiv:1209.5724

Socrates, A., Katz, B., Dong, S., & Tremaine, S. 2012b, ApJ, 750, 106

Takeda, G., & Rasio, F. A. 2005, ApJ, 627, 1001

Triaud, A. H. M. J., Collier Cameron, A., Queloz, D., et al. 2010, A&A, 524, A25

Winn, J. N., Fabrycky, D., Albrecht, S., & Johnson, J. A. 2010, ApJL, 718, L145

Wittenmyer, R. A., Tinney, C. G., O’Toole, S. J., et al. 2011, ApJ, 727, 102

Wright, J. T., Fakhouri, O., Marcy, G. W., et al. 2011, PASP, 123, 412

Wright, J. T., Upadhyay, S., Marcy, G. W., et al. 2009, ApJ, 693, 1084

Wu, Y., & Lithwick, Y. 2011, ApJ, 735, 109

Wu, Y., & Murray, N. 2003, ApJ, 589, 605