DIRECTLY IMAGING TIDALLY POWERED MIGRATING JUPITERS

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ABSTRACT

Upcoming direct-imaging experiments may detect a new class of long-period, highly luminous, tidally powered extrasolar gas giants. Even though they are hosted by ∼Gyr-“old” main-sequence stars, they can be as “hot” as young Jupiters at ∼100 Myr, the prime targets of direct-imaging surveys. They are on years-long orbits and presently migrating to “feed” the “hot Jupiters.” They are expected from “high-e” migration mechanisms, in which Jupiters are excited to highly eccentric orbits and then shrink semimajor axis by a factor of ∼10–100 due to tidal dissipation at close periastron passages. The dissipated orbital energy is converted to heat, and if it is deposited deep enough into the atmosphere, the planet likely radiates steadily at luminosity $L \sim 100–1000 L_{\odot}(2 \times 10^{-7} \sim 2 \times 10^{-6} L_{\odot})$ during a typical ∼Gyr migration timescale. Their large orbital separations and expected high planet-to-star flux ratios in IR make them potentially accessible to high-contrast imaging instruments on 10 m class telescopes. ∼10 such planets are expected to exist around FGK dwarfs within ∼50 pc. Long-period radial velocity planets are viable candidates, and the highly eccentric planet HD 20782b at maximum angular separation ∼0′′08 is a promising candidate. Directly imaging these tidally powered Jupiters would enable a direct test of high-e migration mechanisms. Once detected, the luminosity would provide a direct measurement of the migration rate, and together with mass (and possibly radius) estimate, they would serve as a laboratory to study planetary spectral formation and tidal physics.

Key words: planetary systems – techniques: high angular resolution

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1. INTRODUCTION

Jupiter and Saturn analogs orbiting other Sun-like main-sequence stars have evaded direct detection. With an effective temperature of $\sim 124 \text{ K}$, an extrasolar analog of Jupiter is fainter than a Sun-like host by $\gtrsim 10^8$ in near-IR (Kasting et al. 2009), beyond the reach of instrument capabilities at present and in the near future. While “hot Jupiters” (Jovian planets at $\lesssim 0.1 \text{ AU}$) have high temperatures and thus large planet/star flux ratios, they are too close to their hosts ($\lesssim 0.1 \text{ AU}$) to be spatially resolved by 10 m class telescopes. To date, direct-imaging surveys have focused on searching for long-period massive gas giants around nearby young stars with ages $\lesssim 100 \text{ Myr}$, a strategy that has led to a number of discoveries (e.g., MAROIS et al. 2008; Lagrange et al. 2010). In these systems, the planets are still “hot”—cooling down from presumably high temperatures at birth, which significantly enhances their flux ratios with host stars.

In this Letter, we discuss the possibility of directly imaging a third class of “hot” gas giants (besides close-in hot Jupiters and young Jupiters around young stars), consisting of a population of long-period, very luminous, tidally powered planets undergoing orbital migration.

2. HIGH-ECCENTRICITY MIGRATION DUE TO TIDAL DISSIPATION

It is commonly believed that progenitors of hot Jupiters are formed with semimajor axis $a$ beyond the “snow line” at a few AU and then migrate inward to their current locations by shrinking $a$ by a factor of $\sim 10–100$ (Lin et al. 1996). One class of proposed migration mechanisms involves exciting long-period Jupiters to highly eccentric orbits, due to gravitational interactions with stellar or planetary perturbers, enabling them to lose orbital energy at successive close periastron passages through tidal interactions with their host stars. Such “high-e” mechanisms include KOZAI–LIDOV cycles plus tidal friction (KCTF; WU & MURRAY 2003; FABRYCKY & TREMAINE 2007), planet–planet scatter (Rasio & Ford 1996), “secular chaos” (Wu & Lithwick 2011), etc. Recently, high-e mechanisms have gained observational support. A significant fraction of hot Jupiters are found to be on misaligned orbits with respect to their host stars’ spin axes (WINN et al. 2010; TRIAUD et al. 2010), which is a natural consequence of such mechanisms (Fabrycky & Tremaine 2007).

One general expectation from all high-e mechanisms is that there should exist a steady-state migrating population of long-period, highly eccentric gas giants “feeding” the hot Jupiters (SOCRATES et al. 2012). This results from the continuous generation of hot-Jupiter progenitors due to constant formation of stars and their planetary systems over the age of the Galaxy. The orbital angular momentum is approximately conserved during tidal dissipation, so the actively migrating Jupiters have $a(1 - e^2) \equiv a_{\text{eq}}$, where $a_{\text{eq}} \lesssim 0.1 \text{ AU}$ is the semimajor axis of their final circularized orbit. According to Socrates et al. (2012), the frequency of this population is likely an increasing function of their period (and the eccentricity), extending to that of their “source” (possibly at $\gtrsim 5 \text{AU}$). A possible archetype of the migrating population is HD 80606b (Naef et al. 2001; Moutou et al. 2009), which is a 4 $M_{\text{Jup}}$ planet at semimajor axis $a = 0.45 \text{ AU}$ and $e = 0.93$ ($a_{\text{eq}} = 0.06 \text{ AU}$), accompanied by a solar-mass companion at $\sim 1200 \text{ AU}$.

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Regardless of the specifics of the high-e mechanisms, a gas giant that migrates from semimajor axis \( a' \) to \( a \) over a time \( \Delta t_m \) loses orbital energy due to tidal dissipation, which is converted to heat and radiated away. This leads to an averaged tidal luminosity:

\[
L_m = \frac{GM_s M_p}{2 \Delta t_m} \left( \frac{1}{a} - \frac{1}{a'} \right) \sim 8 \times 10^{26} \text{ erg s}^{-1} \left( \frac{M_s}{M_\odot} \right)
\]

\[
\times \left( \frac{M_p}{3 M_{\text{Jup}}} \right) \left( \frac{\Delta t_m^{-1}}{1 \text{ AU}^{-1}} \right) \left( \frac{\Delta t_m}{1 \text{ Gyr}} \right)^{-1},
\]

(1)

where \( M_s \) is the mass of the host star, \( M_p \) is the mass of the planet, \( \Delta t_m^{-1} = 1/a - 1/a' \). For comparison, \( L_{\text{Jup}} = 8.6 \times 10^{24} \text{ erg s}^{-1} \) is the luminosity of our Jupiter. Fabrycky & Tremaine (2007) present a possible migration path for HD 80606b due to KCTF, and in their simulation, over \( \sim 0.1 \) Gyr, the “migration rate” \( \Delta t_m^{-1}/M_m \) at 0.5 AU, 1 AU, and 2 AU is \( \sim 12, 5, \) and 1.4 \( \text{AU}^{-1} \text{Gyr}^{-1} \), corresponding to \( L_m \sim 1 \times 10^{28}, 5.3 \times 10^{27}, \) and \( 1.5 \times 10^{26} \text{ erg s}^{-1} \), respectively, which span \( \sim 1500–180 \text{ Jup} \) (see also Wu & Murray 2003). If tidal dissipation occurs in a deep enough layer of the planet atmosphere, the thermal relaxation time \( t_h \) can be much longer than the orbital timescale (\( P \sim \) yr), the planet would constantly radiate at its tidal luminosity. The physics of tidal dissipation in giant planets is an unsolved theoretical problem, and there is no reliable method to calculate where the tidal dissipation happens in the planet atmosphere. The upper limit of \( t_h \) is the KEVIN–Hellmoltz timescale \( t_{KH} \propto M_p^2/R_p/L_p \), which is about 0.1 Gyr for a Jupiter with luminosity \( L_p \) at hundreds of \( L_{\text{Jup}} \). For the Jovian planets of interest, \( M_p^2/R_p \) is at most factor of 100 smaller than that for Jupiter, and at this extreme, for \( L_p = 100 \text{ Jup} \), \( t_{KH} \) is still \( \sim \text{Myr} \), much longer than the orbital timescale. The tidal forcing acts on the planet body as a whole, so it is reasonable to expect that significant tidal dissipation operates at a depth that is a considerable fraction of the planet radius and then \( t_h \) is approximately \( t_{KH} \), which is many orders of magnitude larger than the orbital time. We make the reasonable assumption \( t_h > P \) throughout the Letter.

The luminosities of migrating Jupiters can be tidally enhanced by \( \sim 2–3 \) orders of magnitude, comparable to young Jupiters at \( \sim 100 \text{ Myr} \) (Burrows et al. 1997; Baraffe et al. 2003; Marley et al. 2007; Spiegel & Burrows 2012), which are the prime targets for ongoing and planned direct-imaging surveys (Lafrenière et al. 2007a; Liu et al. 2010). These tidally powered Jupiters could be located at \( a \sim \) several \( \text{AU} \), and their maximum separations at apastron are further enhanced by high eccentricity \( e \sim 1 \) by a factor of \((1 + e) \sim 2 \), making them promising targets for direct-imaging detections.

Tidally powered Jupiters are not necessarily limited to those actively migrating at high eccentricity. For example, in the specific cases of KCTF, while the planet visits the highly eccentric phase that enables tidal dissipation at periastroon passages in each Kozai–Lidov cycle, it typically spends much longer (a factor of \( \sim 10 \) more; see Fabrycky & Tremaine 2007) time oscillating at low-eccentricity orbits. The oscillation amplitude in \( e \) is generally larger when the planets are at longer period where relativistic precession is weaker. If the thermal timescale \( t_h \) is longer than the Kozai–Lidov timescale (\( t_{Kozai} \sim 0.02 \text{ Gyr} \) for HD 80606b while migrating at \( \sim 5 \text{ AU} \)), the planet radiates approximately at the averaged tidal luminosity \( L_m \) during the whole Kozai–Lidov cycle. Therefore, the tidally powered Jupiters include not only those at high \( e \) (i.e., small pericenter) but also a factor of \( \sim 10 \) more experiencing Kozai–Lidov oscillations at lower \( e \).

![Figure 1. Planet-to-star contrast ratios for expected tidally powered Jupiter population as a function of angular separations as compared to those reached or expected for current (dotted-dash lines) and upcoming (solid lines) high-contrast imaging instruments for 10 m class telescopes as well as future instruments for 30 m class telescopes (dash lines). The expected H-band contrast ratios at a range of migration rates of 1–10 \text{AU}^{-1} \text{Gyr}^{-1} for 1, 3, and 10 \text{M}_J \) planets are shown in dark green, blue, and yellow shaded regions, respectively. They are calculated using the models in Burrows et al. (1997), as discussed in the text. The maximum angular separation (at apocenter) for a super-eccentric with \( a = 2.7 \text{ AU} \) (snow line for a solar-mass host) at 20 pc is shown as vertical black line with shading, indicating a plausible upper boundary in orbital separations for these Jupiters. Upcoming instruments, such as Subaru/SCESAO, may have substantial sensitivity at small enough angular separations to probe the tidally powered Jupiter population, and high-contrast imaging instruments on future 30 m class telescopes (such as Thirty Meter Telescope (TMT), Giant Magellan Telescope (GMT), and The European Extremely Large Telescope (E-ELT) are expected to have excellent capabilities to detect such planets. The sources for the contrast curves are listed below. (1) Gemini/NICI H band: Liu et al. (2010); (2) Subaru/SCESAO with extreme AO. 1 hr integration: http://www.naoj.org/Projects/newsdev/itn/img/20100426/files/SCESAO_overview_2010-04-26.pdf; (3) Gemini/GPI: http://planetimager.org/index.php?option=com_content&view=article&id=16&Itemid=20; (4) VLT Sphere and ELT EPICS in J band: Kasper et al. (2008); (5) TMT Planet Formation Instrument at 1.65 \( \mu \text{m} \): https://e-reports-ext.llnl.gov/pdf/333450.pdf; and (6) GMT/HRCAM at 1.0 \( \mu \text{m} \) with >1 hr exposure: http://www.physics.berkeley.edu/research/general/Physics250.5/literature-talks/ELT/GMT_Science_Case.pdf. (A color version of this figure is available in the online journal.)

3. DIRECT-IMAGING OBSERVATIONS

The achievable sensitivity of high-contrast imaging instruments degrades substantially within the so-called inner working angle, which is often quoted to be \( \sim 2–4 \) times the diffraction limit, \( \theta_{\text{diff}} \sim \lambda/D \sim 0.02(\lambda/1\mu\text{m})(D/10\text{m})^{-1} \), where \( \lambda \) is the observed wavelength and \( D \) is telescope aperture. Several high-contrast imaging instruments will be commissioned in the near future on a number of 8–10 m telescopes, such as Gemini GPI (Macintosh et al. 2008), VLT SPHERE (Beuzit et al. 2008), Subaru SCESAO (Martinache & Guyon 2009), and LBHT (Hinz et al. 2008). The best contrast goals of these instruments are \( 10^{-7}–10^{-5} \) in near-IR beyond the inner working angle (Macintosh et al. 2008; Beuzit et al. 2008). See Figure 1 for their expected contrast ratio curves in near-IR.

At a migration rate of \( \Delta t_m^{-1}/\Delta t_m = 1–10 \text{AU}^{-1} \text{Gyr}^{-1} \), tidal luminosities for \( \sim 3 \text{M}_J \) planets are \( \sim 2 \times 10^{-7}–2 \times 10^{-6} \text{L}_\odot \) \((\sim 10^2–10^3 \text{Jup})\), corresponding to blackbody effective temperatures \( T_{\text{eff}} \sim 390–690 \text{ K} \) for a planet radius \( 1 \text{R}_\odot \). The peaks of the blackbody radiation at these temperatures
are at \( \sim 9 - 5 \mu \text{m} \). The blackbody contrast ratios at 3.78 \( \mu \text{m} \) (\( L' \) band) of the planet to a Sun-like star (\( T_{\text{eff}} \sim 5800 \text{ K} \)) are \( \sim 5.0 \times 10^{-7} - 3.8 \times 10^{-5} \). At bands further away from the peak (e.g., \( \sim 1 \mu \text{m} \)), blackbody radiation is exponentially suppressed, resulting in very low flux ratios. However, the near-IR spectral energy distribution is unlikely to be well described by blackbody emission. For example, Jupiter has a spectral window allowing for probing deeper, warmer layers of the atmosphere that leads to orders of magnitude larger flux than that of a 125 K blackbody in near-IR (Kasting et al. 2009). We note that according to Burrows et al.’s (1997) model, at effective temperatures 400 K and 600 K, with surface gravity \( 10^4 \text{ cm s}^{-2} \), the contrast ratios in [\( J \), \( H \), \( K \), \( L' \)] bands with a Sun-like star are approximately [3.6 \( \times 10^{-7} \), 4 \( \times 10^{-7} \), 3.9 \( \times 10^{-8} \), 4 \( \times 10^{-8} \)], [3.5 \( \times 10^{-6} \), 4.8 \( \times 10^{-6} \), 1.4 \( \times 10^{-6} \), 2.2 \( \times 10^{-5} \)], respectively. Other models (Baraffe et al. 2003; Spiegel & Burrows 2012) generally predict similar contrast ratios in \( L' \) band, but the predictions can vary by order of magnitude in \( J \) band and \( H \) band, possibly reflecting theoretical uncertainties in such calculations such as the treatment of clouds and planet luminosity evolution.

Socrates et al. (2012) estimate that the frequency of long-period (hundreds of days), highly eccentric Jupiters is about 10% that of hot Jupiters, whose occurrence rate is estimated to be \( \sim 1\% \) around FGK dwarfs (Marcy et al. 2005). Therefore, \( \sim 0.1\% \) of solar-type stars may host this population. There are \( \sim 10^4 \) FGK dwarfs within 50 pc of the Sun, which amounts to \( \sim 10 \) potentially tidally powered Jupiters. The closest super-eccentric Jupiter host is then at \( \sim 20 \) pc, and suppose it starts migration near the snow line at \( \sim 2.7 \) AU, its maximum angular separation is \( \sim 0.27 \) (achieved at apastron for \( e \sim 1 \)), which is marked as a shaded black line in Figure 1.

In Figure 1, the expected ranges of \( H' \)-band contrast ratio assuming migration rate varying from 1 AU\(^{-1} \) to 10 AU\(^{-1} \) Gyr\(^{-1} \) for planets with 1, 3, and 10 \( M_J \) are shown in shaded regions in green, blue, and yellow, respectively. It is challenging for present and most of the upcoming high-contrast imaging instruments such as Gemini/NICI, Gemini/GPI, and VLT/SPHERE to detect the population of tidally powered Jupiters due to their relatively large inner working angles (\( \gtrsim 0.2 - 0.3 \)). The most promising instrument is SCExAO at Subaru. The extreme Adaptive Optics (AO) system of SCExAO is expected to allow for significant sensitivity inside 0.1, which may potentially probe the tidal Jupiters as close as \( a \sim 0.5 \) AU at 20 pc.

One strategy to identify these tidally powered Jupiters is to follow up long-period, highly eccentric planets with known radial velocity (RV) orbits, which are likely to be actively migrating. For \( e \sim 1 \), one obtains maximum projected separation very close to apastron at \( r_{\perp, \text{max}} \approx 2a \sqrt{\sin^2 \omega \cos^2 i + \cos^2 \omega} \), where \( \omega \) is the argument of periastron. There is one RV planet, with \( a \sim 1 \) AU and \( \omega \lesssim 0.1 \) AU, known as HD 20782b (Jones et al. 2006; O’Toole et al. 2009) at 36 pc, and the best-fit parameters are \( M \sin i = 1.9 \) \( M_{\text{Jup}} \), \( a = 1.38 \) AU, \( e = 0.97 \), \( \omega = 148^\circ \) (note that the eccentricity must be confirmed as the periastron passage was not sufficiently probed). It reaches maximum angular separation at (0.28 \( \cos^2 i + 0.72 \) at apocenter, which corresponds to \( \lesssim 2.9 \alpha / D \) at \( J \) band, \( \lesssim 2.2 \alpha / D \) at \( H \) band, \( \lesssim 1.7 \alpha / D \) at \( K \) band, and \( \sim \alpha / D \) at \( L' \) band for a 10 m telescope. The target is difficult to image for most of the current and upcoming high-contrast imaging instruments, but it is likely to be accessible by SCExAO at Subaru given its small expected inner working angle allowed by its extreme AO system (see Figure 1). The long baseline of LBTI (22.8 m) may be advantageous in terms of spatial resolution, but it is challenging given the inner working angle achievable for the current available instrument. It may be accessible when the LBTI high-contrast imaging system is refined (P. Hinz 2012, private communication).

As previously discussed, if KCTF takes place, many long-period, low-\( e \) Jupiters can be tidally powered by radiating heat accumulated from past high-\( e \) visits, and their occurrence rate can be \( \sim 10 \) larger than that of the actively migrating, high-\( e \) population. A possible observation strategy would be to directly image all RV planets with sufficiently large maximum angular separations and probe this population (as well as those that show a linear trend, which indicates the probable presence of long-period planets). Planetary systems with known perturbers from RV residuals or imaging may receive preference since the planets in these system have a higher probability of Kozai–Lidov oscillation. Advanced AO/coronagraph and better post-processing techniques (e.g., Lafrenière et al. 2007b) may help to increase the contrast and decrease the inner working angle.

It may also be possible to remove the speckle noise more efficiently and improve the detection sensitivity with information from the known orbital phase from RV, which will further boost the detectable contrast ratio and obtain smaller inner working angle.

A large fraction of nearby main-sequence stars have not been monitored by RV sufficiently long to find long-period Jupiters. The all-sky astrometric mission \textit{Gaia} is expected to be sensitive to planets more massive than Jupiter between \( \sim 0.5 \) and 3 AU for all solar-type hosts within 50 pc (Lattanzi & Sozzetti 2010), so it will make a nearly complete census of tidally powered Jupiters in the solar neighborhood and provide an excellent sample for direct-imaging follow-ups.

4. DISCUSSION AND FUTURE PROSPECT

If the tidally powered Jupiters are directly imaged, their luminosities provide a direct measure of planet migration rate due to tidal dissipation and thus constrain high-\( e \) migration mechanisms. Combined with RV orbits, one can break the inclination degeneracy in RV to obtain the de-projected true mass and full orbital solution, making them an excellent laboratory to study planetary dynamics. With measured mass and luminosity, one may probe the spectral formation of gas giant atmosphere as well as the physics of tidal dissipation. It is interesting to note that, even though similar high-\( e \) population may exist for binary star (Dong et al. 2012), it is much more difficult to measure tidal luminosity directly due to nuclear burning.

As discussed in Socrates et al. (2012) and Dawson & Johnson (2012), transit surveys such as \textit{Kepler} are ideal to find the eccentric migrating Jupiters due to their enhanced transit probability. Space-based transit surveys that target bright stars may potentially provide an excellent sample of tidally powered planets hosted by nearby stars that are suitable for direct-imaging study. For transiting planets, high-precision IR light curves with secondary eclipse could in principle directly measure the tidal luminosity for these planets as well (see Laughlin et al. 2009).

Ground-based high-contrast imaging instruments are experiencing rapid development over the last few years, and the tidally

\footnote{Note, however, that thermal tidal power generated at pericenter passages could be responsible for tidally powering long-period Jupiters (Arras & Socrates 2009a, 2009b, 2010). In that case, the source of energy is from star light rather than orbit.}
powered Jupiters may turn out to be the most luminous planets to image for nearby solar-type main-sequence stars. New instruments such as SCExAO should already be able to probe this population. Future telescopes such as TMT, GMT, and ELT can conduct a thorough survey for this population around nearby stars due to their smaller diffraction limits (see Figure 1).

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