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HOT JUPITERS IN BINARY STAR SYSTEMS

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ABSTRACT

Radial velocity surveys find Jupiter-mass planets with semimajor axes a less than 0.1 AU around $\sim$1% of solar-type stars; counting planets with a as large as 5 AU, the fraction of stars having planets reaches $\sim$10% (as found by Marcy et al. and Butler et al.). An examination of the distribution of semimajor axes shows that there is a clear excess of planets with orbital periods around 3 or 4 days, corresponding to $a \approx 0.03$ AU, with a sharp cutoff at shorter periods (see Fig. 1). It is believed that Jupiter-mass planets form at large distances from their parent stars; some fraction then migrates in to produce the short-period objects. We argue that a significant fraction of the hot Jupiters ($a < 0.1$ AU) may arise in binary star systems in which the orbit of the binary is highly inclined to the orbit of the planet. Mutual torques between the two orbits drive down the minimum separation or periapsis r_p between the planet and its host star (the Kozai mechanism). This periapsis collapse is halted when tidal friction on the planet circularizes the orbit faster than Kozai torque can excite it. The same friction then circularizes the planet orbit, producing hot Jupiters with the peak of the semimajor axis distribution lying around 3 days. For the observed distributions of binary separation, eccentricity, and mass ratio, roughly 2.5% of planets with initial semimajor axis $a_p \approx 5$ AU will migrate to within 0.1 AU of their parent star. Kozai migration could account for 10% or more of the observed hot Jupiters.

Subject headings: binaries: general — celestial mechanics — planetary systems

1. INTRODUCTION TO KOZAI MIGRATION

Statistics from radial velocity planet searches (Marcy et al. 2005; Butler et al. 2006) show that the occurrence rate of giant planets within 0.1 AU (hot Jupiters) is $\sim$1%; extrapolating to 20 AU the occurrence is 12%. There is a clear "pile-up" of planets with orbital periods near 3 days (Fig. 1). Transit observations yield a similar fraction of hot Jupiters (Gould et al. 2006; Fressin et al. 2007). What migration mechanisms can produce the observed feature in semimajor axis distributions represented by hot Jupiters? In this article we focus on the mechanism known as Kozai migration.

Consider a planet circling a star that is a member of a binary system. The mutual torques between the binary and planetary orbits transfer angular momentum between the two while leaving the orbital energies nearly unchanged. For mutual inclinations $I \gtrsim 40°$ a resonance between the precession rate of the planet's nodal and apsidal lines greatly enhances the effectiveness of this exchange of angular momentum, producing large oscillations in the planet's angular momentum (Kozai cycles; Kozai 1962). The planet eccentricity (e_p) and periapsis [$r_p \equiv a_p(1-e_p)$] oscillate with a characteristic timescale (Holman et al. 1997)

$$P_{\rm Kozai} \approx \frac{m_*}{m_c}\frac{P_c^2}{P_p}\left(1-e_c^3\right)^{3/2}, \qquad (1)$$

where m_* and m_c are the masses of the central and companion stars, while P_c and P_p are the periods of the binary and planetary orbits, respectively. The binary eccentricity is denoted by e_c. Holman et al. (1997) and Takeda & Rasio (2005), among others, have studied the role of these Kozai cycles in producing the eccentricities observed in known exoplanets.

For sufficiently large I, r_p can reach very small values, allowing tidal dissipation to erode the orbit of the planet. Eggleton & Kiseleva-Eggleton (2001) were the first to propose that Kozai cycles, in combination with tidal friction, can shrink the orbit of an inner binary in a hierarchical triple system, leading to the formation of contact binaries. Wu & Murray (2003, hereafter WM03) have studied Kozai migration in application to exoplanets and found it to be the only plausible explanation for the migration of the planetary object HD 80606b.

In the absence of any other modification of the gravitational potential, the minimum r_p may fall below the Roche radius (r_R) and the planet may be destroyed. However, there are a number of competing torques that can limit the amount of angular momentum that the Kozai torque can extract from the orbit of the planet, including general relativistic (GR) corrections to Newtonian gravity, and torques associated with the extended mass distribution of both the primary star and the planet. The latter includes rotationally induced planetary oblateness, the tidal bulge raised by the star on the planet, the misalignment of this bulge produced by friction, and the stellar counterparts of all these. These torques can halt the Kozai-induced collapse in r_p and promote planetary survival.

Which torque becomes competitive with the Kozai torque depends on the system; for systems with a very large binary semimajor axis (a_c) and therefore very weak Kozai torque, the GR precession can halt the reduction of r_p before tides become important. However, for tighter or more inclined binaries, tidal friction sets the minimum r_p. Since the tidal torques depend strongly on r_p, binary systems with a wide range of a_c/a_p will be stalled at essentially the same r_p, leading to a pile-up of hot Jupiters at $a_p \sim 2r_p$ when the planets' orbits are later circularized.

2. NUMERICAL EXPERIMENTS

We quantify the effect of Kozai migration by considering an ensemble of binary systems following that in Takeda & Rasio (2005). These binaries are initially comprised of a solar-mass host star, a Jupiter-mass planet ($m_p = M_J$) orbiting at 5 AU with an eccentricity of 0.05, and a binary companion of mass 0.23 $M_\odot$—this is the peak of the observed mass ratio distribution in the solar neighborhood (Duquennoy & Mayor 1991). The distribution in binary separation [$P(a_c)$] is assumed to be flat in logarithmic a_c (a_c

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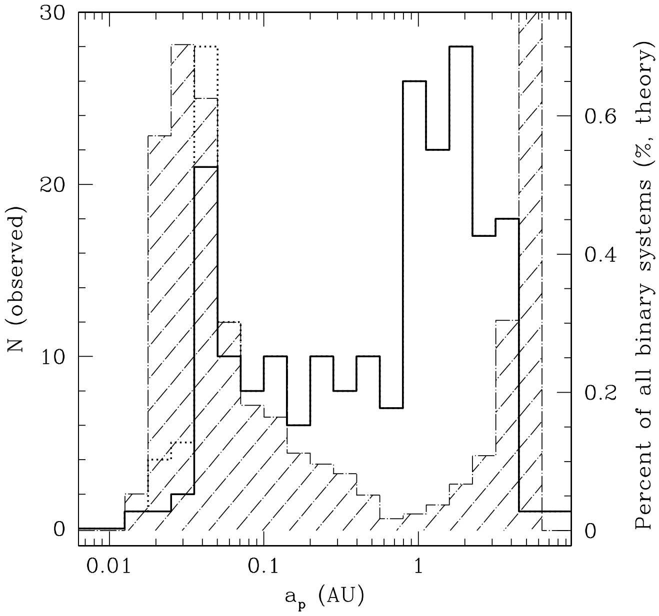

FIG. 1.—Histogram of the planet semimajor axis (logarithmic) distribution. *Thick solid line*: Observed radial velocity planet distribution. The planets detected by the transit technique are added on top (*dotted line*), assuming that the detection efficiencies are the same between the two techniques. The hatched area shows the simulation result, with the vertical axis read at the right. The peak at ~3 day orbital period corresponds to planets that are Kozai migrated and later circularized. The position and width of this peak depends on a number of parameters (see eq. [6]). In particular, if planet radius is a decreasing function of planet age, the width of the peak shrinks (see Fig. 2). The narrow peak at ~5 AU corresponds to planets that are unmigrated, remaining at their initial a_p.

ranging from 20 to 20,000 AU). We set $P(e_b) = 2e_b$, a thermal distribution often adopted in binary population synthesis. This latter choice hardly affects the results. The last *Ansatz*, our most sensitive yet most uncertain assumption, takes I to be isotropically distributed. Based on studies of stellar spin and binary orbits (Hale 1994), this seems reasonable for $a_c > 40$ AU, but may be less appropriate for tighter binaries; polarimetry studies of protostellar disks suggest that the circumstellar disk and the binary plane are correlated for a_c up to a few hundred AU (Jensen et al. 2004; Monin et al. 2006). However, polarimetry estimates only the projected angle between the two planes, and is strongly plagued by interstellar polarization. The results should be taken with caution at present.

We produce an ensemble of 100,000 systems. Out of these we select systems that can potentially perturb the planet to $r_p \lesssim 0.1$ AU. To reach this distance, a planet starting at semimajor axis a_p (with a small eccentricity) will have to attain $e_{\max} \geq 1 - 0.1/a_p$. Ignoring tidal dissipation,[4] the Kozai integral (the planet's orbital angular momentum in the normal of the binary plane) $H_K = (1 - e_p^2)^{1/2} \cos I =$ constant. Taking a minimum $I \approx 40°$ during the Kozai cycles (see, e.g., Holman et al. 1997), this yields a minimum initial inclination required for producing hot Jupiters: $I \gtrsim 81°$. This value is independent of the binary separation or mass. The fraction of isotropically inclined systems that have such a misalignment is ~15%.

We then weed out planets that are likely dynamically unstable according to the following fitting formula:

$$\frac{a_p}{a_c} \geq 0.330 - 0.417 e_c + 0.069 e_c^2. \qquad (2)$$

This expression is obtained by integrating the orbits of our initial system for 10^4 binary orbits, taking $I = 90°$. This non-coplanar stability limit is 15%–30% more restrictive than the coplanar stability limit found by Holman & Wiegert (1999). It is used here as a rough proxy for systems that either eject their planets quickly after formation, or are unable to form planets due to the strong tidal influence of the companion. This procedure eliminates many systems with $a_c < 100$ AU; we are left with ~10% of the original ensemble that could potentially reach <0.1 AU, if they are not stalled by other torques at larger distances.

These remaining systems are integrated using secular equations obtained by averaging over the orbital motions of both the planet and the binary companion (Eggleton & Kiseleva-Eggleton 2001). These equations include the effects of Kozai perturbation, tidal dissipation, GR precession, and tidal and rotational bulge precessions.[5] We use a Runge-Kutta integrator with an adaptive step size set to keep the integration error below a preset limit. We follow the procedure described in WM03, which also lists values for the various parameters involved. In particular, we choose the initial stellar spin direction to be aligned with the initial orbit normal for the planet.

The integration is stopped after 5 Gyr have passed, or when 5 million time steps are exhausted, or when $r_p < 2\ R_\odot$. The last condition roughly corresponds to the planet overflowing its Roche lobe; however, *none* of the planets in our simulation reached this state.[6] The limit on the number of integration time steps is usually reached if Kozai oscillations have been effectively halted by rapid tidal or other precessions; in that case the subsequent dynamical evolution of the planet simply reduces e_p. We then use a simplified code, including only the effects of tidal dissipation on the planet orbit and planet/stellar spins, to finish integrating to 5 Gyr.

We find that about 2.5% of our ensemble eventually migrate inward of 0.1 AU. The distribution of final semimajor axes is concentrated between 0.02 and 0.05 AU with a peak at 0.03 AU. Our hot Jupiters exhibit a pile-up at ~3 day periods similar to the observed population (Fig. 1).

Given the same initial I, tighter binaries produce a closer-in hot Jupiter in a shorter amount of time. Many of the hot Jupiters are tidally ensnared on their first close approach to the host star (Fig. 2), with a Kozai period between 10^4 and 10^8 yr. Tidal circularization of these orbits then takes upward of 10^7 yr.

The 3 day feature in the computed a_p distribution appears wider than the observed distribution. However, as just noted, closer-in planets are migrated in earlier, so they still have larger radii and larger stalling periapsis. Experimenting with the following time evolution of planet radius,

$$R_p = R_J \left[1 + \exp\left(-\frac{t}{\tau_{\rm shrink}}\right)\right], \qquad (3)$$

with $\tau_{\rm shrink}$ taken to be 3×10^7 yr, we find that the 3 day bump narrows significantly (Fig. 3).

3. DISCUSSION

3.1. *Stalling Radius and the 3 day Pile-up*

The periapsis of a Kozai-migrating planet is stalled at a distance where the eccentricity forcing due to the binary companion

[4] Tidal dissipation increases the Kozai integral and slightly raises the minimum requirement on I (WM03).

[5] In this study, we rely exclusively on these secular equations. The actual dynamics may deviate due to short-term noises and mean-motion perturbations and should be studied with N-body integration codes.

[6] This is due to the strong dependence of the tidal timescale on r_p; tidal distortions act as a barrier, maintaining $r_p \gtrsim r_R$.

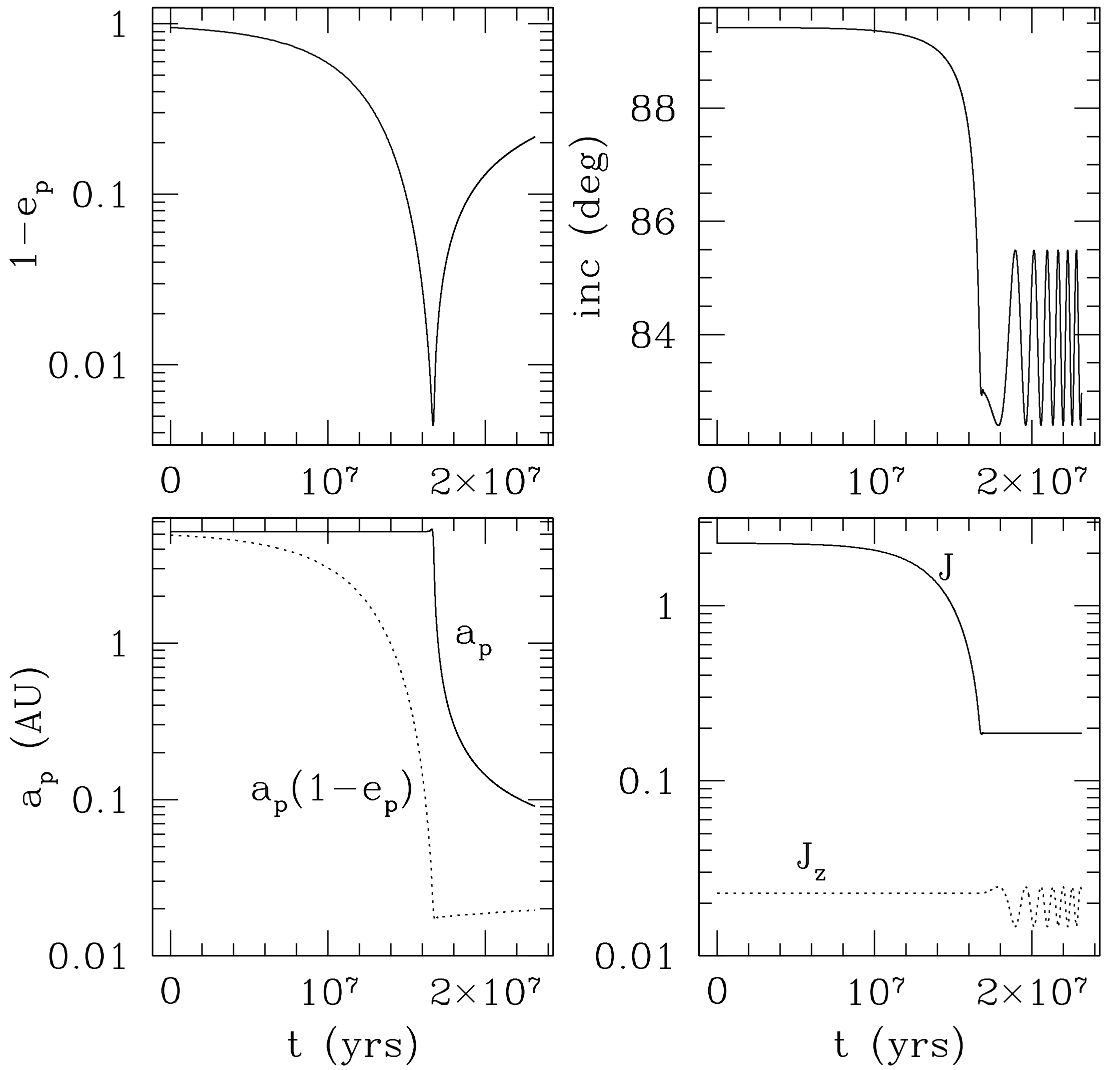

FIG. 2.—Migration history for a system that in the absence of tides would have reached a minimum distance of 0.0004 AU (0.1 $R_\odot$) and been declared lost; in the presences of tides it reaches a minimum distance of 0.013 AU and is later circularized at $a_p = 0.026$ AU. *Top left*: Planet eccentricity as a function of time (in years). *Top right*: Relative inclination between the two orbit normals. *Bottom left*: Planet semimajor axis (*solid line*; in AU) and periapsis (*dotted line*). *Bottom right*: Planet total orbital angular momentum (J; *solid line*) and its component along the orbit normal of the binary (J_z; *dotted line*), both in arbitrary units. Kozai oscillation (which conserves J_z) has proceeded for barely half a cycle before the orbital energy of the planet is significantly dissipated and the planet is removed from the influence of the binary companion. Tidal dissipation operates afterward (during which J is conserved). The inclination angle evolves little in this example.

is counteracted by the eccentricity damping by tidal dissipation. Kozai forcing yields (Eggleton & Kiseleva-Eggleton 2001)

$$\frac{1}{e_p}\frac{de_p}{dt} \approx 5\left(1-e_p^2\right)\frac{m_c n_c^2}{m_p+m_*+m_c}\frac{1}{4n_p\sqrt{1-e_p^2}\left(1-e_c^2\right)^{3/2}}, \tag{4}$$

where $n_c = 2\pi/P_c$, $n_p = 2\pi/P_p$. The rate of tidal eccentricity damping depends strongly on the periapsis distance. Considering only tides raised on the planet, we obtain (Hut 1981)

$$\frac{1}{e_p}\frac{de_p}{dt} \approx -\frac{27k_p G m_p}{2R_p^3 Q_p n_p}\frac{1}{q}\left(1+\frac{1}{q}\right)\left(\frac{R_p}{a_p}\right)^8\frac{1}{\left(1-e_p^2\right)^{13/2}}, \tag{5}$$

where k_p is the planet's tidal Love number, Q_p its tidal dissipation factor, and R_p its radius (see WM03). The mass ratio $q = m_p/m_*$. Equating the two rates, we obtain the stalling periapsis value,

$$r_{p,\rm stall} = 0.015\ \text{AU}\left[\left(\frac{m_*}{M_\odot}\right)^{3/2}\left(\frac{M_{\rm J}}{m_p}\right)\left(\frac{3\times10^5}{Q_p}\right)\left(\frac{k_p}{0.5}\right)\right.$$
$$\left.\times\left(\frac{R_p}{R_{\rm J}}\right)^5\left(\frac{5\ \text{AU}}{a_p}\right)\left(\frac{0.23\ M_\odot}{m_c}\right)\left(\frac{a_c}{270\ \text{AU}}\right)^3\right]^{1/6.5}, \tag{6}$$

where we have scaled variables by their representative values ($R_{\rm J}$ is the radius of Jupiter). Coincidentally, $r_{p,\rm stall} \sim r_R$, and it depends little on a variety of parameters, including stellar mass, companion mass, planet mass, planet tidal Q factor, and planet initial orbit. This justifies our choices for these parameters in the numerical experiment.[7] In our simulation, most binaries that give rise to hot

[7] This mechanism works for other types of planets, such as hot Neptunes or superearths. Substituting into eq. (6) values appropriate for Neptune and Earth, we obtain similar values for $r_{p,\rm stall}$.

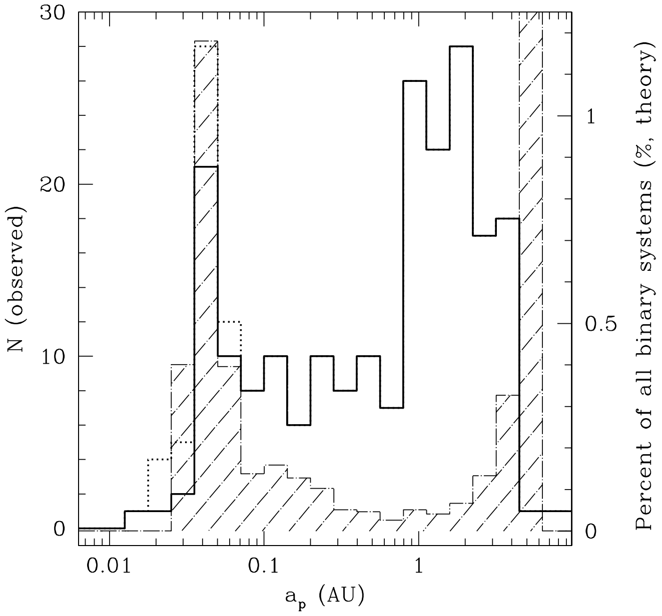

Fig. 3.—Similar to Fig. 1, except where we have taken the planet radius to shrink as $R_p = R_J[1 + \exp(-t/3 \times 10^7 \text{ yr})]$. The 3 day feature narrows significantly.

Jupiters have $a_c \in [100, 1000]$ AU (Fig. 4), and we have scaled a_c here by roughly the median value. Tighter binaries are relatively unimportant—planets in many of these systems are dynamically unstable and are excluded from our study.

In the subsequent tidal circularization, orbital angular momentum is roughly conserved and the final $a_p \sim 2r_{p,\text{stall}} \sim 0.03$ AU.

The fraction of stars with Kozai migrated hot Jupiters is given by

$$f_{<0.1} = f_b f_p f_{\text{Kozai}}, \tag{7}$$

where f_b is the fraction of stars in binary systems, f_p is the fraction of solar-type stars with Jupiter-mass planets formed at a few AU, and f_{Kozai} is the fraction of planets in binary star systems that undergo Kozai migration to $a_p < 0.1$ AU. Taking $f_b \approx 0.65$ (Duquennoy & Mayor 1991), $f_p \gtrsim 0.07$ (Marcy et al. 2005), and $f_{\text{Kozai}} \approx 0.025$ (this work), we suggest that a minimum of 10% of the known hot Jupiters may be due to Kozai migration. The most uncertain number is f_p. The value of f_p we have quoted is the observed fraction in the Keck sample, which is substantially complete up to $a_p \approx 3$ AU. Assuming the number of planets per AU is flat up to $a_p = 30$ AU gives $f_p = 0.12$ and $f_{<0.1} = 0.002$. There is some indication that the number of planets per AU is an increasing function of a_p. If $f_p = 0.5$, more than half the hot Jupiters could be produced by the Kozai mechanism.

3.2. *Predictions of the Kozai Migration Scenario*

The number of hot Jupiters produced by Kozai migration can be determined by observations in the near future, since Kozai migrated planets must have a number of attributes. First, candidate Kozai hot Jupiters will reside in binary star systems, although the binary mass ratio may well be small; a brown dwarf companion can be dynamically as effective as a solar-type companion (eq. [6]). The study by Duquennoy & Mayor (1991) establishes that ~60% of the stars in the solar neighborhood are actually binary or triple systems. While radial velocity surveys select against close binaries, studies by Raghavan et al. (2006) show that at least 23% of radial velocity planet hosts have stellar companions. The discoveries of brown dwarf companions to the planet-bearing stars HD 3651 (Mugrauer et al. 2006) and HD 89744 (Mugrauer et al. 2004) highlight the possibility that the existence of dim companions will increase the known binary fraction of planet-bearing stars significantly. The Kozai scenario predicts that the binary fraction of hot Jupiters will be higher than that of systems with more distant planets.

Binary-induced radial velocity trends induced on the primary by a stellar companion will be of order

$$5f\left(\frac{m_c}{0.3\ M_\odot}\right)\left(\frac{100\ \text{AU}}{a_c}\right)^2 \text{m s}^{-1}\ \text{yr}^{-1}, \tag{8}$$

where f is the sine of the angle between the line of sight and the stellar velocity. This is clearly detectable at the current sensitivity of radial velocity surveys (Wright et al. 2007). The companion will also induce an astrometric acceleration of a few μas yr^{-1} yr^{-1}, detectable by *Space Interferometry Mission PlanetQuest* (*SIM PlanetQuest*) or *Gaia*.

Second, Kozai systems have $I \in [30°, 150°]$, with $I \approx 90°$ not uncommon (Fig. 4). In transiting systems the binary orbit will be in or near the plane of the sky. This can be tested via both radial velocity and astrometry.

Third, the angle between the spin axis of the primary star (assumed to be the orbit normal of the planet at formation) and the present-day planet orbit normal will range from 0° to 130° (Fig. 4) with values between 0° and 50° being preferred. This angle can be determined if both the spin period of the star and its rotational velocity $v \sin i$ can be independently measured. The angle projected onto the plane of the sky, measurable using the Rossiter-McLaughlin effect, will have a similar range.

Fourth, the semimajor axis ratio a_p/a_p' with any second planet will be small. This results from the requirement that the precession rate induced by the second planet not break the Kozai resonance (Wu & Murray 2003). Radial velocity measurements can constrain the mass and semimajor axis of any nearby planetary companions to hot Jupiters (Wright et al. 2007). A corollary is that the fraction of multiplanet systems having hot Jupiters will be smaller than the fraction of single-planet systems with hot Jupiters.

Kozai-migrated planets dissipate many times their own binding energy during tidal circularization. Ogilvie & Lin (2004) find that tidally dissipated energy is deposited throughout the bulk of the planet, raising the possibility that the planet will expand catastrophically. In contrast, Wu (2005) concludes that energy is deposited exclusively near the photosphere, which would leave the planet intact.

The theoretical situation is unclear, but the existence of hot Jupiters suggests an answer. A plot of e_p versus a_p strongly suggests that the low e_p values of the hot Jupiters are the result of tidal circularization, as the observed e_p values follow closely the upper bound set by the tidal process (see, e.g., Fig. 1 of Wu 2003). If so, most or all hot Jupiters have experienced rapid tidal heating and survived.

Another concern with the Kozai picture is raised by the Rossiter-McLaughlin measurement of stellar obliquity, currently available for five transiting planets (see Table 2 of Fabrycky & Tremaine 2007). All are consistent with zero obliquity. Taken at face value, this is at variance with the above Kozai prediction.[8]

[8] HD 147506 (Winn et al. 2007; Loeillet et al. 2007), a 1.3 $M_\odot$ star with a massive planet, may have experienced tidal synchronization in its surface layer that would alter its apparent rotation axis.

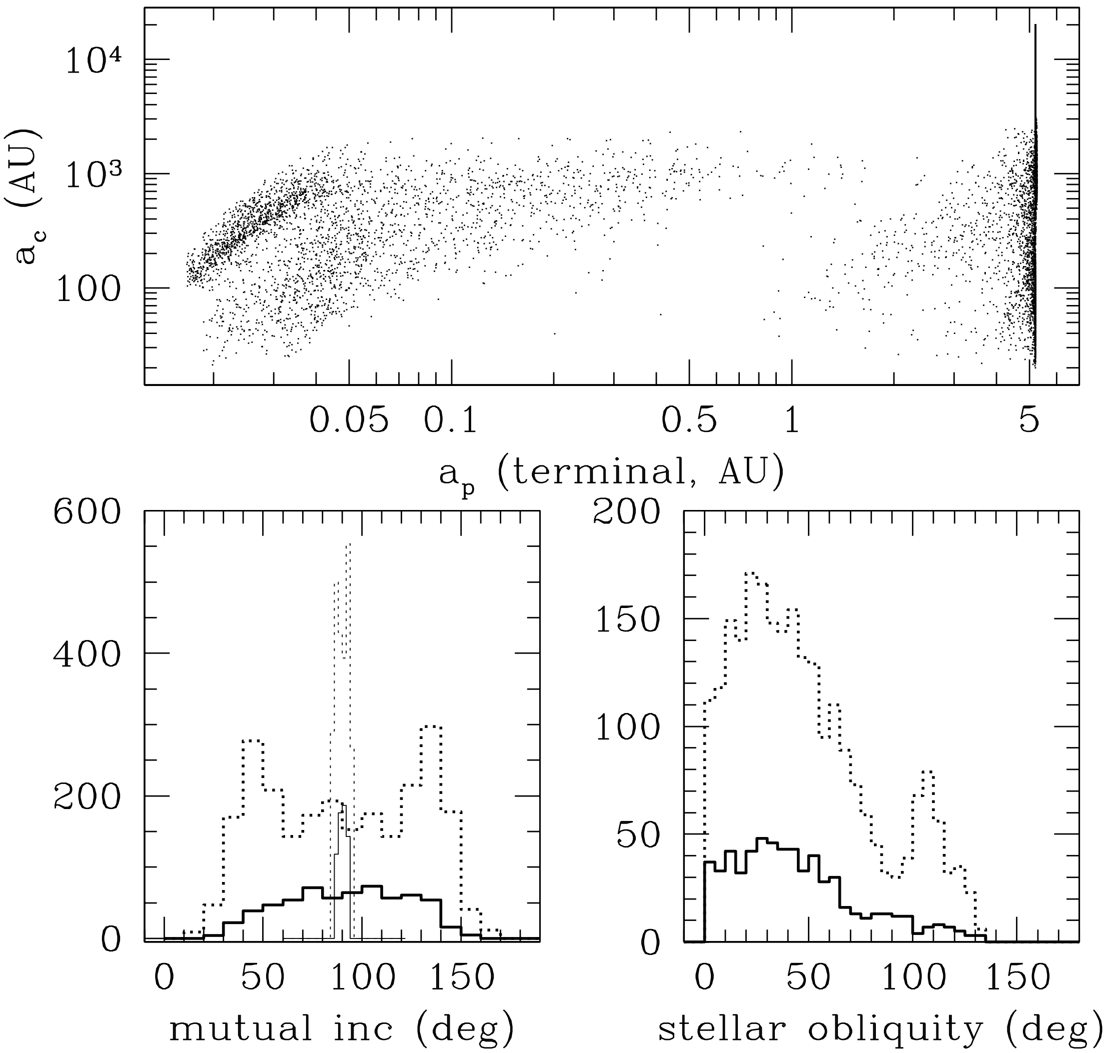

Fig. 4.—Parameters for the binary systems that produce Kozai migration. In the top panel, the final a_p (*horizontal axis*) is plotted against a_c. Smaller values of the former are in general correlated with closer binaries (eq. [6]), with most hot Jupiters arising from binaries with $a_c \in [100, 1000]$ AU. The bottom left panel shows the distributions of initial (*thin lines*) and final (*thick lines*) inclinations between the two orbital planes—the solid lines include systems with $a_p < 0.025$ AU, and the dotted lines all systems with final $a_p < 0.1$ AU (similarly in the right panel). The final inclination angles are much more spread out, as the Kozai cycles convert inclination to eccentricity—Fabrycky & Tremaine (2007) gives a detailed explanation for the features. The bottom right panel shows the distribution of final angles ψ between the stellar spin axis and the planetary orbit normal. Most systems (especially the tightest ones) have $\psi < 50°$, although some stars may spin retrograde relative to the planet orbit.

3.3. *Alternatives to Kozai Migration*

In Kozai migration, it is important that r_p evolves on a timescale no shorter than the tidal precession timescale; if r_p were to suddenly plunge from above to below the Roche radius, as for example would be the case if two planets suffered a close encounter, the inward-scattered planet would not be stalled outside r_R. Instead it would suffer rapid mass loss and likely be lost. In that case there will be a cutoff in the distribution of a_p at $2r_R$ (Ford & Rasio 2006), but not a pile-up.

Migration in a gas disk may also produce hot Jupiters. If the disk extends all the way to the star, one would observe a cutoff at $a_p \sim r_R$; if the disk is truncated, e.g., by stellar magnetic fields (Lin et al. 1996), a feature will appear at an orbital period half that of the inner edge of the disk. However, spin periods and magnetic fields of accreting stars show a substantial dispersion, which would lead to a rather broad distribution in the disk inner radii, and hence a smeared-out feature in the distribution of planetary semimajor axis.

We have studied the role of a binary companion in increasing e_p and causing a gradual collapse in r_p. But it is also plausible that soft planet-planet scattering can gradually decrease r_p (Juric & Tremaine 2007; Chatterjee et al. 2007). Moreover, Kozai oscillations can also be excited by a second planet,[9] in the absence of a binary stellar companion. As long as these or other processes produce gentle eccentricity driving on 10^4–10^8 yr timescales, tidal effects will halt the periapsis evolution when $r_p \sim r_R$. Tidal circularization then pushes the planets out to $a_p \sim 2r_R$ and produces a narrow pile-up of hot Jupiters there.

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[9] This second planet can be placed on a highly inclined orbit by, e.g., planet-planet scattering.

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