LETTER

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Hot Jupiters from secular planet–planet interactions

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About 25 per cent of 'hot Jupiters' (extrasolar Jovian-mass planets with close-in orbits) are actually orbiting counter to the spin direction of the star[1]. Perturbations from a distant binary star companion[2,3] can produce high inclinations, but cannot explain orbits that are retrograde with respect to the total angular momentum of the system. Such orbits in a stellar context can be produced through secular (that is, long term) perturbations in hierarchical triple-star systems. Here we report a similar analysis of planetary bodies, including both octupole-order effects and tidal friction, and find that we can produce hot Jupiters in orbits that are retrograde with respect to the total angular momentum. With distant stellar mass perturbers, such an outcome is not possible[2,3]. With planetary perturbers, the inner orbit's angular momentum component parallel to the total angular momentum need not be constant[4]. In fact, as we show here, it can even change sign, leading to a retrograde orbit. A brief excursion to very high eccentricity during the chaotic evolution of the inner orbit allows planet–star tidal interactions to rapidly circularize that orbit, decoupling the planets and forming a retrograde hot Jupiter.

Despite many attempts[2,3,5–11], there is no model that can account for all the properties of the known hot Jupiter systems. One model suggests that hot Jupiters formed far away from the star and slowly spiralled in, losing angular momentum and orbital energy to the protoplanetary disk[12,13]. This 'migration' process should produce planets with low orbital inclinations and eccentricities. However, many hot Jupiters are observed to be on orbits with high eccentricities and misaligned with the spin axis of the star (as measured through the Rossiter–McLaughlin effect[14]), and some of these (8 out of 32) even appear to be orbiting counter to the spin of the star. In a second model, secular perturbations from a distant binary star companion can produce increases in the eccentricity and inclination of a planetary orbit[15]. During the evolution to high eccentricity, tidal dissipation near pericentre can force the planet's orbit to decay, potentially forming a misaligned hot Jupiter[2,3]. Recently, secular chaos involving several planets has also been proposed as a way to form hot Jupiters on eccentric and misaligned orbits[11]. A different class of models that can produce a tilted orbit involves planet–planet scattering[5], possibly combined with other perturbers and tidal friction[7]. In such models, the initial configuration is a densely packed system of planets and the final tilted orbit is a result of dynamical scattering among the planets, in contrast to the secular interactions we study here.

In our general treatment of secular interactions between two orbiting bodies, we allow the magnitude and orientation of both orbital angular momenta to change (Fig. 1). The outer body (here either a planet or a brown dwarf) gravitationally perturbs the inner planet on timescales long compared to both orbital periods (that is, we consider the secular evolution of the system). We define the orientation of the inner orbit with respect to the invariable plane of the system (the invariable plane is perpendicular to the total angular momentum): a prograde (retrograde) orbit has $i_1 < 90^\circ$ ($i_1 > 90^\circ$), where i_1 is the angle between the inner orbit's orbital angular momentum vector and the total angular momentum vector. Note that the word 'retrograde' is also used in the literature to indicate orbital motion counter to the stellar spin. The directly observed parameter is actually the projected angle between the spin axis of the star and the orbital angular momentum of a hot Jupiter. Our proposed mechanism can produce hot Jupiters that are 'retrograde' with respect to both the stellar spin and the total angular momentum. By contrast, a distant stellar companion can only succeed in the former (see Supplementary Information for details): here we will use the term 'retrograde' in only one sense, that is, to indicate an orbit with $i_1 > 90^\circ$, as defined above.

We assume a hierarchical configuration, with the outer perturber on a much wider orbit than the inner one. In the secular approximation,

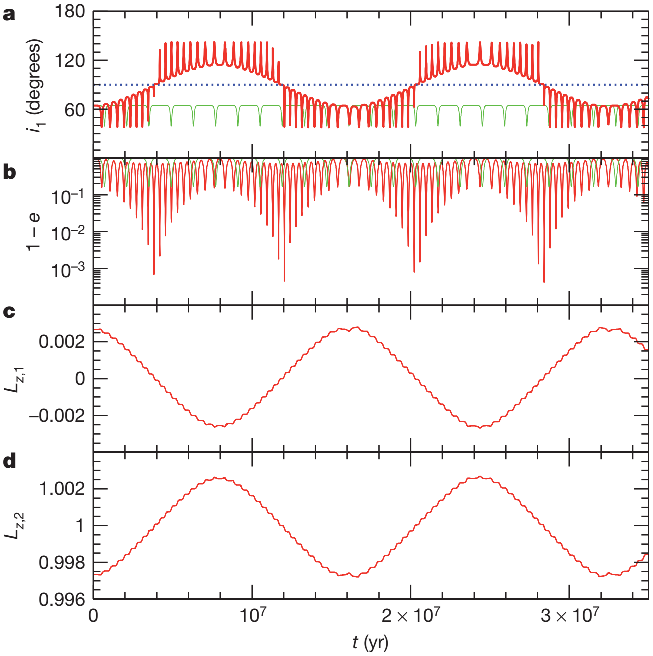

Figure 1 | Dynamical evolution of a representative planet and brown dwarf system. Here we ignore tidal dissipation, but we do include the lowest-order post-Newtonian precession rate for the inner orbit. The star has mass $1M_\odot$, the planet has mass $1M_J$ and the outer brown dwarf has mass $40M_J$. The inner orbit has $a_1 = 6$ AU and the outer orbit has $a_2 = 100$ AU. The initial eccentricities are $e_1 = 0.001$ and $e_2 = 0.6$, and the initial relative inclination is $i = 65^\circ$. Red curves show the following: **a**, the inner orbit's inclination, i_1; **b**, the eccentricity of the inner orbit (as $1 - e_1$); and **c**, **d**, the z-component of the angular momentum of the inner ($L_{z,1}$; **c**) and outer ($L_{z,2}$; **d**) orbit, normalized to the total angular momentum (where the z-axis is defined to be along the total angular momentum). The dotted line in **a** marks the 90° boundary, separating prograde and retrograde orbits. The initial mutual inclination of 65° corresponds to an inner and outer inclination with respect to the total angular momentum (parallel to z) of 64.7° and 0.3°, respectively. During the evolution, the eccentricity and inclination of the inner orbit oscillate, but, in contrast to what would be predicted from evolution equations truncated to quadrupole order (shown by green curves in **a** and **b**), the eccentricity of the inner orbit can occasionally reach extremely high values and its inclination can become higher then 90°. The outer orbit's inclination always remains near its initial value. We note that more compact systems usually do not exhibit the same kind of regular oscillations between retrograde and prograde orbits illustrated here, as chaotic effects become more important and are revealed at octupole order (see Fig. 2). We find that for ~50% of the time, the inner orbit is retrograde.

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the orbits may change shape and orientation but the semi-major axes are strictly conserved in the absence of tidal dissipation[4,16]. In particular, the Kozai–Lidov mechanism[17–19] produces large-amplitude oscillations of the eccentricity and inclination when the initial relative inclination between the inner and outer orbits is sufficiently large ($40^\circ < i < 140^\circ$).

We have derived the secular evolution equations to octupole order using Hamiltonian perturbation theory[4,20,21]. In contrast to previous derivations of 'Kozai-type' evolution, our treatment allows for changes in the z-components of both orbital angular momenta (that is, the components along the total angular momentum), $L_{z,1}$ and $L_{z,2}$, where 1 and 2 refer to the inner and outer orbits, respectively (see Supplementary Information). The octupole-order equations allow us to calculate the evolution of systems with more closely coupled orbits and with planetary-mass perturbers. The octupole-level terms can give rise to fluctuations in the eccentricity maxima to arbitrarily high values[4,21], in contrast to the regular evolution in the quadrupole potential[2,3,19], where the amplitude of eccentricity oscillations is constant.

Many previous studies of secular perturbations in hierarchical triples considered a stellar-mass perturber, for which $L_{z,1}$ is very nearly constant[2,3,19]. Moreover, the assumption that $L_{z,1}$ is constant has been built into previous derivations[22,23,24]. However, this assumption is only valid as long as $L_2 \gg L_1$, which is not the case in comparable-mass systems (for example, with two planets). Unfortunately, an immediate consequence of this assumption is that an orbit that is prograde relative to the total angular momentum always remains prograde. Figure 1 shows the evolution of a representative system (here without tidal effects for simplicity): the inner planet oscillates between prograde and retrograde orbits (with respect to the total angular momentum) as angular momentum flows back and forth between the two orbits.

Previous calculations of planet migration through 'Kozai cycles with tidal friction'[2,3,16,19] produced a slow, gradual spiral-in of the inner planet.

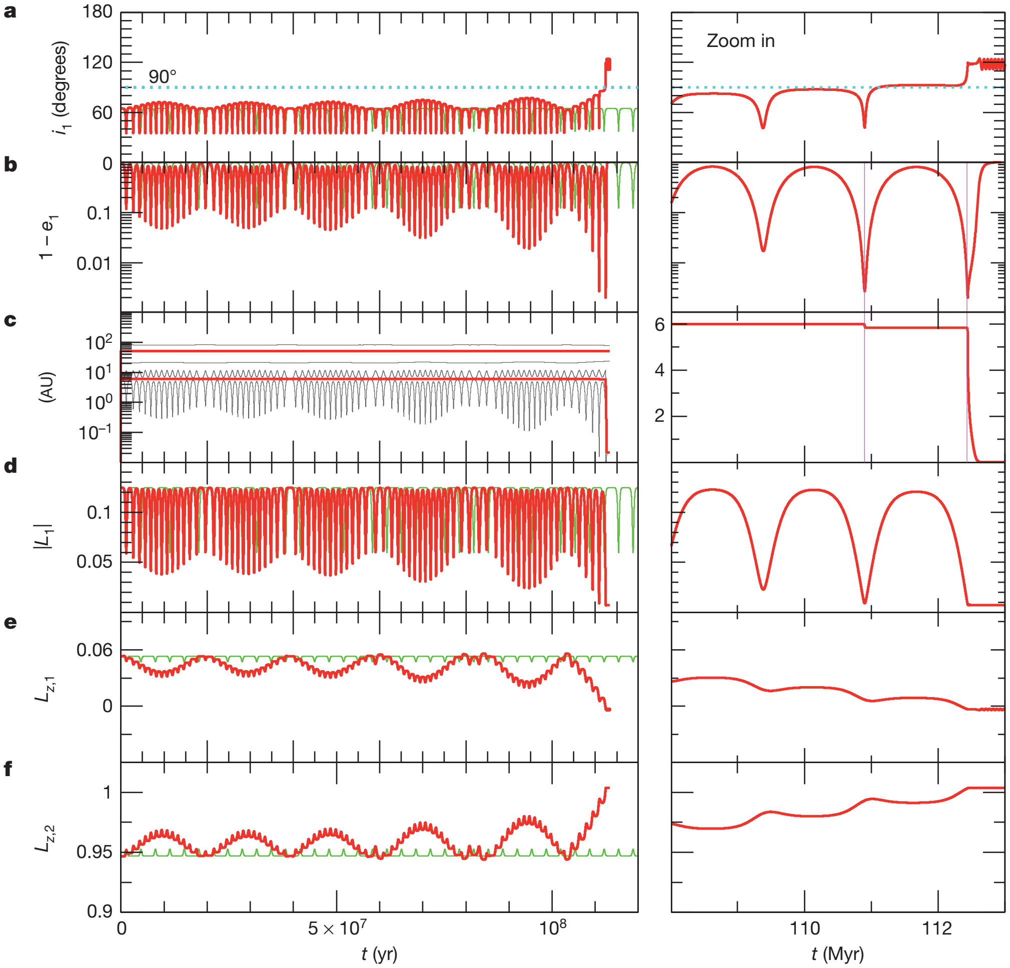

Figure 2 | Dynamical evolution of a representative two-planet system with tidal dissipation included. The inner planet becomes retrograde at 112 Myr, and remains retrograde after circularizing into a hot Jupiter. Here the star has mass $1M_\odot$, the inner planet has mass $1M_J$ and the outer planet has mass $3M_J$. The inner orbit has $a_1 = 6$ AU and the outer orbit has $a_2 = 61$ AU. The initial eccentricities are $e_1 = 0.01$ and $e_2 = 0.6$, the initial relative inclination $i = 71.5^\circ$, and the argument of periapsis is 45°. Left panels, complete simulation; right panels, zoomed-in view around time $t \approx 110$ Myr. Red curves show: **a**, the inner orbit's inclination (i_1); **b**, the eccentricity of the inner orbit (as $1 - e_1$); **c**, the semi-major axis for the inner orbit and the outer orbit; **d**, the magnitude of the angular momentum of the inner orbit; and in **e** and **f**, the z-component of the angular momentum of the inner ($L_{z,1}$; **e**) and outer ($L_{z,2}$; **f**) orbit, normalized to the total angular momentum. The black curves in **c** are the pericentre and apocentre distances of the inner and outer orbits, respectively. The initial mutual inclination of 71.5° corresponds to inner- and outer-orbit inclinations of 64.7° and 6.8°, respectively. During each excursion to very high eccentricity for the inner orbit (marked with vertical lines in **b** and **c** right panels), tidal dissipation becomes significant. Eventually the inner planet is tidally captured by the star and its orbit becomes decoupled from the outer body. After this point, the orbital angular momenta remain nearly constant. The final semi-major axis for the inner planet is 0.022 AU, typical of a hot Jupiter. The green curves in **a**, **b**, **d**, **e** and **f** show the evolution in the quadrupole approximation (but including tidal friction), demonstrating that the octupole-order effects lead to a qualitatively different behaviour. For the tidal evolution in this example, we assume tidal quality factors $Q_* = 5.5 \times 10^6$ for the star and $Q_J = 5.8 \times 10^6$ for the hot Jupiter (see Supplementary Information). We monitor the pericentre distance of the inner planet to ensure that it always remains outside the Roche limit[29]. Here, as in Fig. 1, we also include the lowest-order post-Newtonian precession rate for the inner orbit.

Instead, our treatment shows that the eccentricity can occasionally reach a much higher value than in the regular 'Kozai cycles' calculated to quadrupole order. Thus, the pericentre distance will occasionally shrink on a short timescale (compared to the Kozai period), and the planet can then suddenly be 'tidally captured' (that is, the inner orbit suddenly decouples from the outer one, and undergoes rapid tidal circularization) by the star. We propose to call this 'Kozai capture'.

Kozai capture provides a new way to form hot Jupiters. If the capture happens after the inner orbit has flipped, the hot Jupiter will appear in a retrograde orbit. This is illustrated in Fig. 2. During the evolution of the system, the inner orbit shrinks in steps (Fig. 2c) whenever the dissipation becomes significant, that is, near unusually high eccentricity maxima. The inner orbit can then eventually become tidally circularized. This happens near the end of the evolution, on a very short timescale (see Fig. 2, right panels). In this final step, the inner orbit completely and quickly decouples from the outer perturber, and the orbital angular momenta then become constant. Therefore, the final semi-major axis for the hot Jupiter is $\sim 2r_p$, where r_p is the pericentre distance at the beginning of the capture phase[25].

The same type of evolution shown in Fig. 2 is seen with a broad range of initial conditions. There are two main routes to forming a hot Jupiter through the dynamical evolution of the systems we consider here. In the first, tidal friction slowly damps the growing eccentricity of the inner planet, resulting in a circularized, prograde hot Jupiter. In the second, a sudden high-eccentricity spike in the orbital evolution of the inner planet is accompanied by a flip of its orbit. The planet is then quickly circularized into a retrograde short-period orbit. We can estimate the relative frequencies of these two types of outcomes using Monte Carlo simulations. Given the vast parameter space for initial conditions, a complete study of the statistics is beyond the scope of this Letter (but see S.N. *et al.*, manuscript in preparation). However, we can provide a representative example: consider systems where the inner planet was formed *in situ* at a distance from the star of $a_1 = 6$ AU with zero obliquity (that is, it orbits in the stellar equatorial plane) and with some small eccentricity $e_1 = 0.01$, while the outer planet has $a_2 = 61$ AU. The masses are $m_1 = 1M_J$ and $m_2 = 3M_J$ (M_J is the Jovian mass). We draw the eccentricity of the outer orbit from a uniform distribution and the mutual inclination from a distribution uniform in cos i between 0 and 1 (that is, isotropic orbits among prograde ones). For this case we find that, among all hot Jupiters that are formed, about 7% are in truly retrograde motion (that is, with respect to the total angular momentum) and about 50% are orbiting counter to the stellar spin direction. Note that the latter fraction is significantly larger than the values previous studies have obtained with stellar-mass perturbers (at most ~10%; refs 2, 3). The high observed incidence of planets orbiting counter to the stellar spin axis[1] may suggest that planet–planet secular interactions are an important part of their dynamical history.

Our mechanism requires that two coupled orbits start with a relatively high mutual inclination ($i > 50°$). In Fig. 2, the outer planet is initially on a very wide orbit, similar to those of directly imaged planets such as Fomalhaut b (ref. 26) and HR 8799b (ref. 27). The inner planet's initial location is consistent with *in situ* formation on a nearly circular orbit, in accordance with the standard core accretion model[28]. An alternative path to such a configuration involves strong planet–planet scattering in a closely packed initial system of several giant planets[7]. Independent of any particular planet formation mechanism, we predict that systems with misaligned hot Jupiters should also contain a much more distant massive planet or brown dwarf on an inclined orbit.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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