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HOT JUPITERS' TIDAL INTERACTION WITH THEIR HOST STARS

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RESUMEN

De los casi 120 planetas extrasolares con masas similares a la de Júpiter, algunos son planetas calientes semejantes a Júpiter con períodos inferiores a 1-2 semanas y órbitas casi circulares. La interacción de marea entre estos planetas y su estrella anfitriona conlleva a la circularización de sus órbitas y a un límite en su distribución de períodos. Además, también causa un calentamiento de marea interno y a mayores tamaños esperados, como se ha inferido de las observaciones del planeta que transita alrededor de HD 209458.

ABSTRACT

Some of the nearly 120 known Jupiter-mass extrasolar planets are hot Jupiters with periods less than 1-2 weeks and nearly circular orbits. Tidal interactions between these planets and their host stars lead to the circularization of their orbits and a cut off in their period distribution. In addition, it also causes planets' internal tidal heating and larger than expected sizes as inferred from the observation of a transiting planet around HD 209458.

Key Words: **PLANETS AND SATELLITES: GENERAL — STARS: PLANETARY SYSTEMS — STELLAR DYNAMICS**

One of the surprising findings in the search for planetary systems around other stars is the discovery of extrasolar planets with periods down to 3 days (Mayor & Queloz 1995). Around approximately one per cent of all the stars targeted by radial-velocity searches, similar planets are found with periods of a few days. These short-period planets were probably formed within a protostellar disk several AU away from their host stars through a sequence of physical processes outlined in the conventional 'core-accretion' theories of planetary formation (Lissauer 1993; Pollack et al. 1996). During its final accretion phase, strong interactions between a protoplanet and its natal disk lead to the formation of a gap near its orbit, which effectively terminates its growth. Angular momentum exchange with the disk causes a protoplanet formed in the inner region of the disk to migrate towards its host star (Goldreich & Tremaine 1980; Lin & Papaloizou 1986). Near the star, the protoplanet's migration may be halted either by its tidal interaction with a rapidly spinning host star or by entering a cavity in the disk associated with the stellar magnetosphere (Lin, Bodenheimer, & Richardson 1996).

Short-period planets may be scattered to the vicinity of (or far away from) the stellar surface owing to dynamical instabilities associated with their long-term post-formation gravitational interaction (Rasio & Ford 1996; Weidenschilling & Marzari 1996). In this case, the protoplanet's orbit may initially be highly eccentric and subsequently undergo circularization owing to the tidal dissipation within its envelope (Rasio et al. 1996). The observational data on the orbital parameters of these planets are particularly useful for differentiating some scenarios for the formation and evolution of short-period planets. For example, the apparent minimum cut-off period may be due to their migration stopping mechanism or a tidal disruption front (Gu *et al.* 2003). While the eccentricities of planets with periods $P > 21$ days are uniformly distributed up to about 0.7, all planets with $P < 7$ days have nearly circular orbits. This observed dichotomy in the eccentricity–period distribution has been attributed to the circularization of the orbits of short-period planets induced by their internal tidal dissipation (Rasio et al. 1996; Marcy et al. 1997). Such a scenario would be necessary to account for the small eccentricities of the short-period planets if they were scattered into, or strongly perturbed in, the vicinity of their host stars by their planetary siblings. If, instead, the short-period planets acquired their small semi-major axes through tidal interaction with their natal disks (Lin et al. 1996), such a process may be able to damp the eccentricities of planets with masses $M_p \lesssim 10\,M_J$ (where M_J is the mass of Jupiter) (Goldreich & Tremaine 1980; Artymow-

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icz 1992), although this hypothesis remains uncertain (Papaloizou, Nelson, & Masset 2001; Goldreich & Sari 2003). However, some of the potential stopping mechanisms, such as the planets' tidal interaction with rapidly spinning host stars, can also excite their orbital eccentricities (Dobbs-Dixon, Lin, & Mardling 2004). An efficient post-formation eccentricity damping mechanism may still be needed to account for the small eccentricities of the short-period planets.

Tidal interaction can also modify the radii and internal structures of short-period planets. In principle, the actual sizes of extrasolar planets may be used, at least as a partial test, to infer whether they formed through core accretion or through gravitational instability of massive gaseous protostellar disks. The detection of a transiting planet around the star HD 209458 provides an opportunity for us to measure its radius directly and thereby to constrain its present internal structure. The observed radius, $1.35\, R_J$, of this $0.63\, M_J$ planet (Brown et al. 2001) is larger than that expected for a coreless planet with a similar mass and age. A planet with a core would be still more compact, leading to an even larger discrepancy with the observational measurement. For this short-period planet, the presence of a small residual orbital eccentricity or non-synchronous rotation could lead to internal tidal dissipation with a heating rate comparable to or larger than that released by the Kelvin–Helmholtz contraction (Bodenheimer et al. 2001).

There are at least two other scenarios for the unexpectedly large size of HD 209458b. Heating by stellar irradiation reduces the temperature gradient and the radiative flux in the outer layers of short-period planets. This process could significantly slow down the Kelvin-Helmholtz contraction of the planet and explain the large size (Burrows *et al.* 2000). However, even though the stellar flux onto the planet's surface is 5 orders of magnitude larger than that released by the gravitational contraction and cooling of its envelope, this heating effect alone increases the radius of the planet by about 10%, not by 40% as observed (Guillot & Showman 2002).

An alternative source is the kinetic heating induced by the dissipation of the gas flow in the atmosphere which occurs because of the pressure gradient between the day and night sides. In order to account for the observed size of the planet, conversion of only 1% of the incident radiative flux may be needed, provided that the dissipation of induced kinetic energy into heat occurs at sufficiently deep layers (tens to 100 bars). Showman & Guillot (2002) suggest that the Coriolis force associated with a synchronously spinning planet may induce the circulation to penetrate that far into the planet's interior, and that dissipation could occur through, for example, Kelvin-Helmholtz instability. A follow-up analysis suggests that this effect may be limited (Burkert *et al.* 2004).

These different scenarios can be tested with observation of transiting hot Jupiters. In order to account for the observed size of HD 209458b, the tidal inflation scenario requires not only a sufficient rapid dissipation rate but also an adequate energy source to maintain this state. These requirements lead to the prediction of its small eccentricity and presence of a hypothetical planet (Bodenheimer *et al.* 2001). The residual scatter in the current RV data set for HD 209458b is consistent with the presence of an as-of-yet undetected second companion (Bodenheimer *et al.* 2003). Three other transiting planets (Konacki *et al.* 2003; Bouchy *et al.* 2004) have even shorter orbital periods. Both the irradiation and kinetic heating scenarios predict that they should have even larger radii. Their actual observed radii are smaller than HD 209458b.

In order to further study the tidal inflation scenario, Gu *et al.* (2003) showed that while the tidal dissipation rate is a rapidly increasing function of the size of Jupiter-mass planets R_p, the surface luminosity increases even faster with R_p. Therefore, the planets with relatively small eccentricities and modest to long periods attain a state of thermal equilibrium in which the radiative loss on their surface is balanced by the tidal dissipation in their interior. For planets with short periods and modest to large eccentricities, the rate of interior heating is sufficiently large that their R_p may inflate to more than two Jupiter radii. In this limit, the surface luminosity of the planet becomes a less sensitive function of its R_p and the eccentricity damping rate is smaller than the expansion rate of the planet so that the increases in their surface cooling rate cannot keep pace with the enhanced dissipation rate due to their inflated sizes. These planets are expected to undergo runaway inflation and mass loss.

In their initial calculations, Gu *et al.* (2003) assume that the tidal dissipation occurred well below the planet's photosphere. In a follow-up study, Gu *et al.* (2004) examine 1) how does tidal energy dissipation actually lead to the expansion of the envelope? 2) how does the internal structure of the planet depend on the distribution of their internal tidal dissipation rate? and 3) what are the important physical effects which determine the tidal inflation stability of the planets? In the gaseous envelope of these planets, efficient convection enforces a nearly adiabatic stratification. During their gravitational contraction, the planets' radii are determined, through the condition of a quasi-hydrostatic equilibrium, by their central pressure. In interiors of mature, compact, distant planets, such as Jupiter, degeneracy pressure and the non-ideal equation of state determine their structure. But, in order for young or intensely heated gas giant planets to attain quasi-hydrostatic equilibria, with sizes comparable to or larger than two Jupiter radii, their interiors must have sufficiently high temperature and low density such that degeneracy effects are relatively weak. Consequently, the effective polytropic index monotonically increases whereas the central temperature increases and then decreases with the planets' size. These effects cause the power index of the luminosity's dependence on radius to decrease with increasing radius. For planets larger than twice Jupiter's radius, this index is sufficiently small that they become thermally unstable to tidal inflation.

Gu *et al.* (2004) also consider the possibility of localized tidal dissipation and study shell-heating models. Such a process may occur in differentially rotating planets or near the interface between the convective and radiative zones where the wavelength associated with dynamical tidal response is comparable to the density scale height. Localized dissipation may also occur through the dissipation of resonant inertial waves or radiative damping in the atmosphere. The unheated planet's interior in strong shelling-heating cases might still be inflated due to a significant expansion of the gas above the heating zone, although the overall expansion rate is less efficient than that in the uniform heating cases as a result of a greater amount of radiative loss from the planet's photosphere. Without gaining entropy, the expanding interior cannot lift its degeneracy and therefore cannot increase its elasticity. However, the gas above the shell-heating zone can lift its non-ideal properties and hence enhance its elasticity in that region, possibly leading to the thermal runaway as the planet expands.

The above discussion indicates the importance of planet–star tidal interactions to the origin and destiny of short-period planets. They may determine (1) the asymptotic semi-major axis of migrating protoplanets, (2) the abundance of hot Jupiters, (3) the structure of those planets that survive in the vicinity of their host stars, and (4) the small eccentricities and relatively low masses of the short-period planets. However, the efficiency of these processes depends on the ability of the planet to dissipate tidal disturbances, which is poorly understood. A gaseous planet maintains a state of quasi-hydrostatic equilibrium as it adjusts to the varying gravitational potential of its orbital companion. In the extended convective envelopes of gaseous giant planets and low-mass stars, turbulence can lead to dissipation of the motion that results from the continual adjustment of the equilibrium tide. However, the turbulent viscosity estimated from the mixing-length theory ought to be reduced by a frequency-dependent factor owing to the fact that the convective turnover timescale is usually much longer than the period of the tidal forcing (Goldreich & Nicholson 1977).

In rapidly spinning body, inertial waves can be excited by the Coriolis force which provides a restoring effect to a general disturbance (Greenspan 1968). The same process leads to low-frequency oscillations in an adiabatically stratified convective envelope of a spinning gaseous planet with frequencies (as observed in the rotating frame) no greater in magnitude than twice the angular velocity of the fluid. The surface layer of hot Jupiters may be stabilized against convection because they are intensely heated by their host stars and may attain a radiative state. If so, g-mode oscillations may be excited in the radiative layer just above its interface with the planet's convective envelope and dissipated through radiative or nonlinear damping (Lubow, Tout, & Livio 1997). The tidal perturbation can strongly amplify these waves and excite normal modes.

The dissipation occurs both through the viscous or turbulent dissipation of the inertial waves in the convective region and through the emission of generalized Hough waves that propagate through the radiative envelope towards the surface, where they presumably damp. Enhancement of the tidal dissipation rate, through a dynamical tide, constitutes a mostly wavelike correction to the equilibrium tide. The enhanced dissipation implies a more rapid synchronization of the planet's spin with its orbit, a faster circularization of the orbit, and a more intense heating of the planet. The actual dissipation location depends sensitively on the internal structure of the planet. In planets with cores, the dynamical tide takes the form of an indirectly forced inertial wave confined in a spherical annulus. Ogilvie & Lin (2004) have presented the results of full numerical calculations of the tidal response for an idealized model of a giant planet that is predominantly convective but also contains a solid core and has a thin radiative envelope.

Examination of the spatial structure of the tidal response in the convective region shows, in line with work by Rieutord et al. (2001) on free inertial waves in an incompressible fluid contained in a spherical annulus, that the disturbance is localized near rays, which are the characteristics of the spatially hyperbolic equations governing inertial waves, and are seen to reflect many times from the inner and outer boundaries. The rays are straight or curved depending on whether the planet rotates uniformly or differentially. In the limit of small viscosity, the intensity of tidal dissipation is highly frequency dependent (Ogilvie & Lin 2004). When the forcing and response frequencies are in resonance, the energy dissipation rate is intense whereas between the resonances spin frequency, Brunt–Väisälä frequency distribution, the adiabatic index, and equation of state also evolve. Since all of these physical effects contribute to the planets' dynamical response to the tidal perturbation from their host stars, their response and resonant frequencies are continually modified. The structure of the planet adjusts on a radiation transfer time scale which generally differs from the time scale for a planet to evolve through the non resonant region. In addition, the tidal forcing frequency also changes as the planets evolve toward a state of synchronous spins and circular orbits. Therefore, it is more appropriate to consider a frequency averaged tidal dissipation rate. In the limit of small viscosity, the frequency averaged dissipation rate converges such that the equilibrium tidal dissipation formula may be a reasonable approximation.

In the limit of a very small solid core, the tidal response is much less rich and is concentrated at frequencies that coincide accurately with those of free inertial modes in a full polytropic sphere, as calculated by Lockitch & Friedman (1999). In this case, partial internal reflection of the inertial waves may occur at any discontinuity of density associated with a putative first-order phase transition between the metallic and molecular regions in Jupiter. Through its effect on the ray propagation inside the planet, such internal reflection could alter the tidal response in a significant way. Without the converging rays, the dissipation of tidal disturbance may occur near the planets' surface (Wu & Arras in preparation), in which case, the circularization process does not necessarily lead to planetary inflation and disruption. An accurate measurement of the sizes of close-in young Jupiters via planet transit surveys can be used to constrain the theories of tidal dissipation and hence internal structure for these objects.

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