# Interactions between Hot Jupiters and Their Host Stars

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**Abstract.** A young hot Jupiter might have been tidally inflated beyond its Roche radius when its orbit was being circularized. This scenario has the potential to explain a couple of solid or tentative observations such as a pile-up of hot Jupiters around 0.04-0.05 AU, the mass-period correlation of transiting planets, as well as the existence of hot Neptunes. Other scenarios such as tidal dissipation in a planet-host star as well as the magnetic interaction will be also discussed.

**Key words:**



## 1. Introduction

More than 140 extrasolar Jupiters have been discovered (http://obswww.unige.ch/˜udry/planet/planet.html) since the first discovery of a Jovian planet 51 Peg b around a solar-type star via the Doppler measurement a decade ago (Mayor & Queloz 1995). Most of the extrasolar planets were detected through Doppler measurements. A few of the very close-in Jupiters were found via transit methods. One of the most intriguing results is that while there exists a *pile-up* of planets around 0.04-0.05 AU (referred to as the hot Jupiters with orbital periods of 3-4 days) from their solar-type host stars, the abundance of extrasolar Jupiters inside 0.04 AU (referred to as very hot Jupiters) is *low* (Gaudi et al. 2005). A number of models have been proposed to explain the "3-day Jupiter desert". Most of them are attributed to three types of interactions: gravitational interactions (tides), magnetic interactions, and stellar irradiation (mass loss of a hot Jupiter due to evaporation). For the topic of evaporation, I refer the readers to the recent work by Baraffe et al. 2005. Tidal effects and the possible magnetic stress caused by a hot Jupiter crossing the coronal field lines will be the focus of this paper.

## 2. Tides in planet-host stars

The dissipative process of tidally locking a solar-type star by its close planetary companion could alter the orbital size depending on the age of the planetary system. When embedded in a protostellar disk, a hot Jupiter might stop inward migration due to the tidal torque exerted from the young fast-rotating star (Lin et al. 1996). However as the star ages and therefore becomes a slow rotator as a result of magnetic braking, the hot Jupiter might lose its orbital angular momentum via the tides in the planet-host star and hence move towards the star (Patzold & Rauer 2002; Jiang et al. 2003). These scenarios are subject to the unknown efficiency of tidal dissipation in solar-type stars. The tidal efficiency may be parameterized by the quality factor $Q$ (Goldreich & Soter 1966). In this section, we concentrate only on the tidal efficiency of main-sequence solar-type stars excited by hot Jupiters.

If the paucity of very hot Jupiters is caused by efficient tides in their host stars, the 3-day cut-off orbital period for the hot Jupiters implies that the quality factor $Q_{star}$ of a solar-type star at the age of a few Gyrs is of the order of $10^{5-6}$ (Jiang et al. 2003). This value for $Q_{star}$ is consistent with the one inferred from the cutoff periods for orbital circularization of stellar binaries in old stellar clusters (Mathieu et al. 2004). It also seems to agree with the observation that the stars with hot Jupiters have not yet rotated abnormally faster than the stars without hot Jupiters, except for $\tau$ Boo which hosts a more massive hot Jupiter (Barnes 2001). However, this also means that studying the rotation periods of the stars currently hosting hot Jupiters cannot verify this $Q_{star}$ value since magnetic braking dominates the evolution of stellar rotation.

The discovery of the very hot Jupiter around the late F-type main-sequence star OGLE-TR-132 offers a constraint

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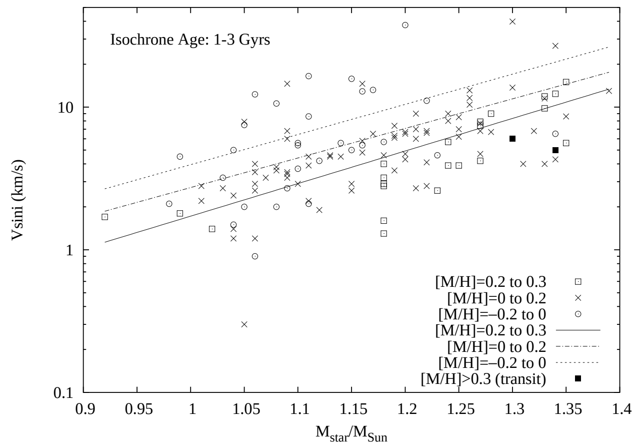


**Fig. 1.** $Vsini$ as a function of the stellar mass $M_{star}/M_{Sun}$ and the metallicity [M/H] for the stars at the age of 1-3 Gyrs. Although the uncertainty in isochrone ages and a large scatter due to sin$i$, there still exists a systematic increase in $V$sin$i$ as [M/H] decreases.

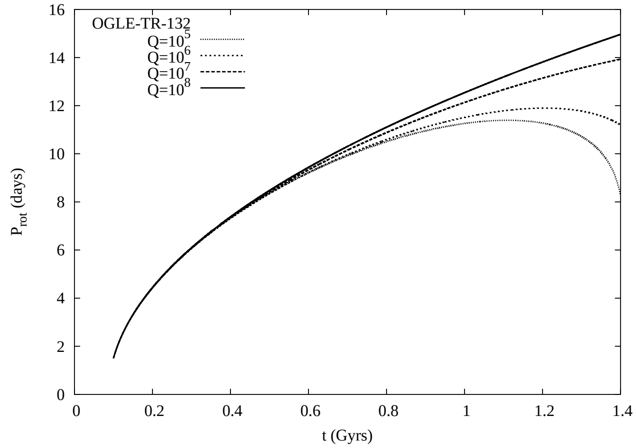


**Fig. 2.** Evolution of $P_{rot}$ for OGLE-TR-132 in the cases of 4 different $Q_{star}$ values as shown in the legend. We adopt the following stellar and planetary parameters: the wind parameter $K_w = 6.3$. $M_{star} = 1.337 M_{Sun}$, $R_{star} = 1.46 R_{Sun}$, and $M_p = 1.01 M_J$.

to the tidal efficiency of a solar-type, or strictly speaking, a late F-type star. This is because if $Q_{star} \sim 10^6$, the magnetic braking time scale is comparable to the tidal spin-up time scale for a star having a thinner convection zone and hosting an extremely close-in Jupiter. Fig. 1. shows the projected rotation velocity $V$sin$i$ of the stars at the isochrone age of 1-3 Gyrs in terms of the stellar mass $M_{star}/M_{Sun}$ and the global metallicity [M/H] using the California-Carnegie planet survey data from Valenti & Fischer 2005. The plot shows a clear trend that more massive stars rotate faster, consistent with the notion that magnetic braking is less efficient for a more massive solar-type star of a thinner convection zone. The distribution of the stars of different metallicity is fitted to 3 different curves in Fig. 1. in order to distinguish the effect of metallicity on the rotation of stars. The 3 fitting curves are already divided by the mean value of sin$i$=$\pi/4$ to take into account the average effect introduced by the random viewing angle $i$ in an ensemble. Although the uncertainty in isochrone ages and a large scatter due to sin$i$, there still exists a systematic increase in $V$sin$i$ as [M/H] decreases; namely, for the stars of the same age and mass, metal-poor stars rotate faster than metal-rich stars owing to the thinner convection zone and therefore weaker magnetic braking. The two filled square points in Fig. 1. are the metal-rich stars OGLE-TR-132 (on the right) and HD 149026 (on the left) having transiting planets, and therefore their sin$i \approx 1$ assuming that the rotation axis is tidally aligned with the normal of the orbital plane. Note that the rotation velocity 5 km/s, corresponding to $P_{rot} \approx 15$ days, for OGLE-TR-132 is a maximum value (Bouchy et al. 2004). Compared with HD 149026 and the fitting curves for the stars without very hot Jupiters, OGLE-TR-132 hosting a very hot Jupiter does not show the evidence of tidal spin-up but appears to be a slow rotator among the stars of ≈ 1.35 $M_{Sun}$ due to its high metallicity.

The evolution of the rotation angular velocity $\Omega$ and the semi-major axis $a$ is governed by the equations

$$\frac{\dot{\Omega}}{\Omega} = \frac{1}{\tau_{tide,\Omega}} - \frac{1}{\tau_{wind}}, \qquad \frac{\dot{a}}{a} = -\frac{1}{\tau_{tide,a}}, \tag{1}$$

where $\tau_{tide,a}$ and $\tau_{tide,\Omega}$ are the e-folding timescales for the change of $a$ and $\Omega$ due to tidal synchronization, and $\tau_{wind}$ is the spin-down time scale of the star due to magnetic braking following the Skumanich relationship (Skumanich 1973). Similar to the free parameter $Q_{star}$ that describes the efficiency of the tidal effect (i.e. $\tau_{tide,\Omega} \propto Q_{star}$), another calibration parameter $K_w$ specifies the strength of magnetic braking (i.e. $\tau_{wind} \propto 1/K_w$). Fig. 2. shows the evolution of the rotation period $P_{rot} = 2\pi/\Omega$ for OGLE-TR-132 in the cases of 4 different $Q_{star}$ values. Without tidal dissipation, $K_w$ equals 6.3 for OGLE-TR-132 to spin down to $P_{rot} = 15$ days at its current age $\approx 1.4$ Gyrs (i.e. $Q_{star} = \infty$, or see $Q_{star} = 10^8$ in Fig. 2. for approximation). Fig. 2. shows that $Q_{star} = 10^6$ together with $K_w = 6.3$ cause $P_{rot} < 12$ days, which differs from the observation $P_{rot} > 15$ days unless a higher $K_w \leq 11.6$ is adopted. We calibrate $K_w$ based on Figure 4 in Barnes 2003 and found that $K_w = 11.6$ is a value for the spectral type beyond K-type.

In summary, the rotation velocity of the late F-type star OGLE-TR-132 indicates that either tidal efficiency is lower than what is expected from main-sequence binaries or magnetic braking is abnormally efficient due perhaps to its extremely high metallicity. Abnormal magnetic braking is doubtful since as shown in Fig. 2., another similar metal-rich star HD 149026 does not have a negligible rotation velocity.

## 3. Tides in young hot Jupiters

Although observations show that the orbits of hot Jupiters are almost tidally circularized over a few Gyrs, most of the extrasolar planets have the eccentricities larger than 0.2. This implies that a young hot Jupiter might still have large eccentricity and undergo intense tidal heating due to its large eccentricity and size. The 7-day cut-off orbital period for the eccentricity distribution of extrasolar planets at the age of a few Gyrs suggests that $Q_J \approx 10^6$, a value similar to that for our Jupiter excited by Io (Yoder & Peale 1981). Fig. 3. shows the evolution of a tidally inflated hot Jupiter calculated from

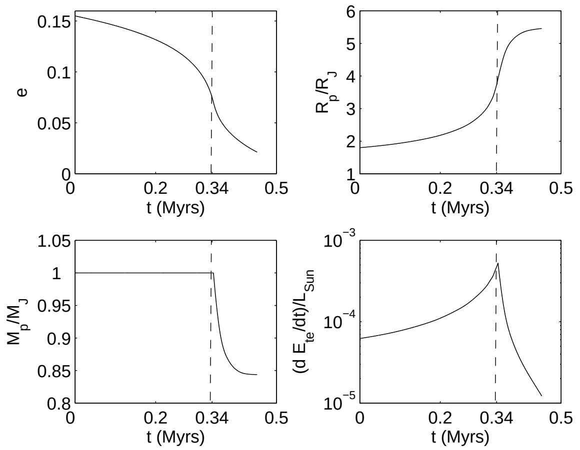


**Fig. 3.** Evolution of a tidally inflated hot Jupiter with $Q_J = 10^6$ and a constant heating rate per unit mass. $e$ is the eccentricity, $R_p/R_J$ is the planet's radius in units of Jupiter radius, $M_p/M_J$ is the planet's mass in units of Jupiter mass, and $(dE_{te}/dt)/L_{Sun}$ is the tidal dissipation in units of solar luminosity. The dashed line marks the onset of Roche-lobe overflow.

the 1-D simulation for the interior structure of a young hot Jupiter (Gu et al. 2003). $Q_J = 10^6$ and the assumption of a constant heating rate per unit mass are adopted. The inward migration due to the protostellar disk as well as atmospheric evaporation driven by stellar irradiation are not considered. The planet of one $M_J$ with an initial $e = 0.16$ and $a = 0.03$ AU can be inflated by tidal heating to its Roche radius over 0.34 Myrs. After that, the planet loses mass, gains specific angular momentum, and then moves to $a = 0.04$ AU. The simulation stops when the overflow stops. This occurs when the planet starts to contract as the eccentricity damps and therefore detaches from its expanding Roche radius. The tidal inflation results from the thermal instability for a planet larger than $\approx 2R_J$ (i.e. a young Jupiter) with a large eccentricity. The increase in the cooling rate of a young Jupiter is reduced as the planet is inflated. This arises from the physics that the interior structure evolves from a stiff equation of state to a soft one as the planet is inflated.

Gu et al. 2004 take into account other uncertainties in the model: 1) tidal heating is not concentrated at the center of a planet but is deposited in a thin spherical shell, 2) the effect of opacity in the radiative layer of the planet on the inflation. Current models on the equilibrium and the dynamical tides suggest various locations of tidal heating (Lin & Gu 2004). If tidal heating is deposited in a thin shell with only 10% of the total mass above it, a planet of one $M_J$ at $a = 0.04$ AU requires $e = 0.28$ (a value higher than the one for the case of a constant heating per unit mass) to be inflated to its Roche radius. The planet will not reach its Roche radius if the same amount of heating is deposited to the radiative-convective boundary or above, as a result of the leak of more energy. Likewise, a planet of low opacity in its radiative envelop does not inflate as efficiently as the one of high opacity.

By this scenario, the progenitors of a pile-up of hot Jupiters are the tidally inflated Jupiters which lost mass inside 0.04 AU due to intense tidal heating and moved out to 0.04-

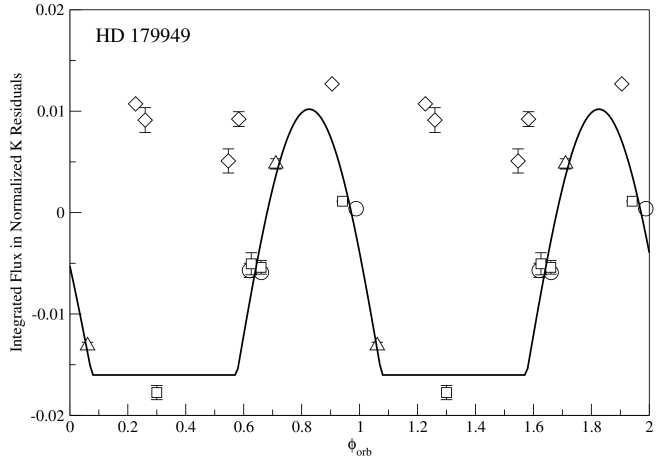


**Fig. 4.** Integrated flux of the K-line residuals from a normalized mean spectrum of HD 179949 as a function of orbital phase. The symbols distinguish data from from different observing runs: circles – 2001 August, squares – 2002 July, triangles – 2002 August, diamonds – 2003 September (Shkolnik et al. 2005).

0.05 AU. Since the time scale of the tidal inflation ($<$ 1 Myr) is less than the disk lifetime ($\approx$ a few Myrs), these progenitors should migrate to the "3-day Jupiter desert" at the time when the disk is being dissipated. This raises two issues. First of all, for the Jupiter-mass planets which migrated to the vicinity of the stars earlier than the time when the disk starts to dissipate, they would have reduced a significant amount of mass since they spent a longer time inside 0.04 AU due to the disk torque. Disruption of Jupiter-mass planets in the tidal inflation scenario matches another different theoretical result that 90% of hot Jupiters have perished for some reasons based on the formation model (Ida & Lin 2004). Besides, the tidal inflation model has the potential to explain the existence of hot Neptunes (McArthur et al. 2004; Santos et al. 2004) which might be the remaining core of a tidally inflated hot Jupiter. The second issue is a hot Jupiter in a multiple planet system such as $\upsilon$ Andromeda. During the phase of disk dissipation, the eccentricity of the hot Jupiter's orbit might be greatly excited by the secular resonance under the influence of mutual perturbation among planets, general relativity, the fast rotating host star, and the decaying disk potential (Nagasawa & Lin 2005). The survival of a hot Jupiter in a multiple planet system against the tidal inflation needs to be investigated.

## 4. Magnetic Interaction

The synchronous enhancements of Ca II H & K emission with the short-period planetary orbits of HD 179949 and $\upsilon$ And ($P_{rot} = 3.092$ and 4.617 day, respectively) have been detected (Shkolnik et al. 2003, 2005). Fig. 4. shows the variability of Ca II emission as a function of the orbital phase of HD 179949 based on the data from different observing runs. $P_{rot}$ of HD 179949 is 7-10 days (Shkolnik et al. 2005). The 2001 and 2002 data are fitted to a truncated sine curve as if a hot spot in the star's chromosphere is induced by the orbiting planet and leads the location of the planet by $\approx 60°$. The energy associated with the enhanced emission of the fitting curve in Fig. 4. is the same order of magnitude as a typical solar flare, $\sim 10^{27}$ erg/s. Although only from one observing run, the 2003 data (denoted by diamonds in Fig 4) suggests that the synchronous enhancement is weaker and the leading phase is smaller when the average Ca II emission is stronger. This effect seems to be related to the stellar cycle.

One of the possible scenarios to explain enhanced emission, phase difference, and changes with the stellar cycle is the magnetic interaction that occurs as the hot Jupiter orbits across and therefore perturbs the coronal field lines. A hot Jupiter at 0.04-0.05 AU is probably located inside the Alfv́en radius of its solar-type host star (Zarka et al. 2001, Ip et al. 2004, Shkolnik et al. 2005, Preusse et al. 2005) such that the Alfv́en wave disturbance excited by the hot Jupiter crossing the field lines can travel against stellar winds toward the host star. Since the input energy carried by the Alfv́en disturbance launched from the magnetopause of the planet due to the magnetic stress is much smaller than the energy enhancement in Ca II emission $\sim 10^{27}$ erg/s (Shkolnik et al. 2005), the enhanced emission, which has the magnitude of the same order as a solar flare, may be reasonably interpreted as the release of the intrinsic magnetic energy already stored on the surface of a star. The energy release is triggered by the planet-induced Alfv́en disturbance. It is not surprising that fast rotating late F-type stars such as HD 179949 and $\upsilon$ And were observed to exhibit the synchronous enhancements because fast rotators build up the magnetic energy more efficiently. The phase difference between the peak of the enhanced emission and the location of the planet is therefore a result of winding coronal fields of a fast rotating star in this scenario. As the star becomes more active, the coronal hole shrinks and the stellar open fields are restricted to the magnetic polar region of the star. During this phase, the induced Alfv́en waves traveling along the open fields trigger the energy release near the magnetic polar regions, leading to the weaker enhanced emission and the smaller phase difference due to the tilted viewing angle and faster Alfv́en speeds. On the other hand, $\upsilon$ And exhibited very weak enhanced emissions in the 2001 observing run (Shkolnik et al. 2005) due probably to the star's low chromospheric activity in that year. Another planet-host late F-type star $\tau$ Boo has $P_{rot}$ close to $P_{orb}$, resulting in essentially little magnetic interaction and therefore no observed synchronous enhancement as the hot Jupiter crosses the stellar field lines.

If the energy enhancement in Ca II emission $\sim 10^{27}$ erg/s is mostly extracted from the orbital energy of hot Jupiters, very hot Jupiters would finally plunge into their host stars over a few Gyrs (Shkolnik et al. 2005). However, this effect on the planet's orbit is small if the Ca II enhancement is intrinsically from the star itself as speculated in the "triggering" scenario described in the above paragraph.

In addition to the magnetic interaction in old planetary systems, the interaction should be much more intense due to stronger stellar (and/or planetary) fields in young systems. When the system is still embedded in a protostellar disk, the strong stellar fields might open an inner cavity in the disk and stop inward planet migration (Lin et al. 1996). Besides the noisy variability in H$\alpha$ or X-ray due to accretion in these young disk systems, the existence of regular variability might suggest the presence of a young hot Jupiter.

## 5. Summary

No sign of tidal spin-up of OGLE-TR-132 and the energy budget constrained from the synchronous enhancement of Ca II for HD 179949 suggest that the "3-day Jupiter desert" is not attributed to the orbital decay due to tides in planet-host stars and magnetic interaction. There is a tentative correlation that the mass of the transiting gaseous planets discovered to date increases as the orbital period $P_{orb}$ decreases (Mazeh et al. 2005; Konacki et al. 2005). The argument of stopping inward migration of a young Jupiter by the truncation of the inner part of a proto-stellar disk by stellar magnetic fields (Lin et al. 1996) does not seem to be easily connected to the planet mass to explain the correlation. On the other hand, mass loss due to evaporation by stellar irradiation is also difficult to lead to the relation (Mazeh et al. 2005). In the tidal inflation model, the correlation can be produced as tidally inflated planets lose mass and move away from their host stars. As a result, some of hot Jupiters appear to gather around 0.04-0.05 AU, and others with a large $e$ might have tidally lost most of their gaseous envelop to form hot Neptunes.

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