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# Thermal Tides: An Explanation for the Inflated Radii of the Hot Jupiters

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## Abstract

As a newly discovered class of astrophysical objects, the hot Jupiters provides some clearly-posed, but difficult to explain, physical problems. The inferred radii of transiting hot Jupiters are far too large to be explained by internal heating due to passive gravitational contraction. A subtle tidal mechanism resulting from asymmetric day-night heating, known as "thermal tides," leads to asynchronous spin in the steady state. The ongoing dissipation of the gravitational tide provides the necessary internal dissipation required to inflate hot Jupiters for the lifetime of the system. The basic physics of thermal tides in gas giant fluid planets as well as a description of how this mechanism may be important in understanding the observed properties of the hot Jupiters will be given.

## 1. Introduction

Hot Jupiters are clearly inflated above their zero-temperature radii and typically, their gravitational contraction times are significantly shorter than the age of their host star. It follows that a persistent and powerful source of heat, responsible for internal luminosities up to $10^{28}$ erg/s, must be at work in these objects. Arras and Socrates [1],[2] show that thermal tidal forcing in hot Jupiters induce large quadrupole moments that, when coupled to the tidal potential of the host star, leads to a torque that accelerates the planet away from synchronous spin. As the planet's spin period shortens, the amount of radiant energy absorbed per cycle decreases and the rate of acceleration away from synchronous spin decreases with time. Ultimately, the thermal tidal torque becomes small enough that the gravitational tidal torque – responsible for de-spinning the planet – halts further acceleration and an asynchronous spin equilibrium is reached (see Figure 1).

Persistent asynchronous spin implies persistent gravitational tidal dissipation. The level of asynchronous spin generated by thermal tidal torques quantitatively leads to tidal dissipation rates that can power the inflated radii of the hot Jupiters i.e., accounting for the radius excess of even the most inflated objects.

The ultimate source of energy is starlight. Upon absorption, stellar heating moves material across the tidal potential and performs work. An amount of work that is equal to the energy dissipated per cycle by the gravitational tide.

## 2. Thermal tides in Fluid Bodies

On a more fundamental level, thermal forcing from the stellar radiation field excites fluid motion in the planet. Arras and Socrates [2] show that in order to accurately compute the quardupole moments induced by thermal forcing, the inertia of the fluid must be taken into account. That is, a dynamical theory of thermal tides is required.

Given the structure of heavily irradiated gas giant planets, the fluid response from thermal forcing is primarily due to the excitation of internal oscillation modes. Each oscillation mode can be thought of as obeying a homogeneous wave equation

$$\frac{\partial^2 \psi_\alpha}{\partial t^2} + \omega_\alpha^2 \psi_\alpha = 0 \qquad (1)$$

where $\psi$ is a fluid quantity such as the linear pressure perturbation. External driving at a forcing frequency $\sigma$ provides a source of wave energy $S(\mathbf{x};\sigma)$. The forced response $\psi$ is given by an integral of the product of the Green's function $G(\mathbf{x},\mathbf{x}')$ and the source, over the planet

$$\psi(\mathbf{x}) = \int d^3x'\, G(\mathbf{x},\mathbf{x}')S(\mathbf{x}') \qquad (2)$$

where the Green's function can be conveniently written in terms of a sum over the $\psi_\alpha$'s [3]

$$G(\mathbf{x},\mathbf{x}') = \sum_\alpha \frac{\psi_\alpha^*(\mathbf{x}')\psi_\alpha(\mathbf{x})}{\omega_\alpha^2 - \sigma^2}. \qquad (3)$$

The "overlap" integral

$$\mathcal{I}_\alpha = \int d^3x\, \psi^*_\alpha(\mathbf{x})\, S(\mathbf{x}) \tag{4}$$

quantifies the efficiency at which the external forcing $S(\mathbf{x};\sigma)$ excites a given mode. The shape of the thermal forcing is such that low order g-modes with oscillation periods of order $\sim$ a few days are preferentially excited by thermal forcing in hot Jupiters. Coincidentally, the forcing periods for these systems, which is roughly given by the orbital period, is close to the eigen-frequencies of the modes that have the highest overlap with the external thermal forcing [2].

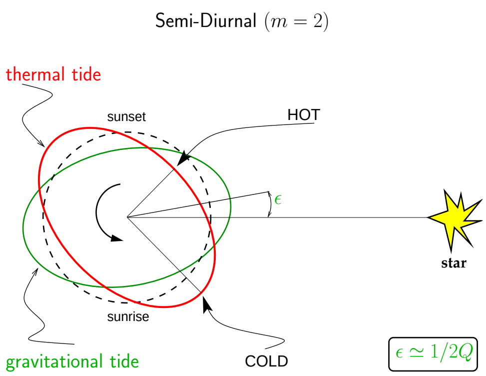


Figure 1: Diagram of thermal and gravitational tidal action in competition. Here, $Q$ is the tidal quality factor. Thermal forcing in general produces a quadrupole that is off-set from the line joining the planet and the star. The tidal potential of the star can then torque the thermal tide quadrupole, which increases the spin of the planet. The thermal tidal torque is subsequently balanced by the gravitational tidal torque and the resulting spin state is asynchronous. On-going gravitational tidal dissipation is presumed to be the source of power at great depth.

## References


[1] Arras, P., & Socrates, A. 2009, arXiv:0901.0735

[2] Arras, P., & Socrates, A. 2010, ApJ, 714, 1

[3] Jackson, J. D. 1998, Classical Electrodynamics, 3rd Edition, by John David Jackson, pp. 832. ISBN 0-471-30932-X. Wiley-VCH , July 1998.,