Concerning thermal tides on hot Jupiters

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ABSTRACT

By analogy with a mechanism proposed by Gold and Soter to explain the retrograde rotation of Venus, Arras and Socrates suggest that thermal tides may excite hot jovian exoplanets into nonsynchronous rotation, and perhaps also noncircular orbits. It is shown here that because of the absence of a solid surface above the convective core of a jovian planet, the coupling of the gravitational and thermal tides vanishes to zeroth order in the ratio of the atmospheric scale height to the planetary radius. At the next order, the effect probably has the sign opposite to that claimed by the latter authors, hence reinforcing synchronous and circular orbits.

Subject headings: hydrodynamics—binaries: close—planetary systems—stars: oscillations, rotation

1. Introduction and Discussion

The thermal tide in an orbitally circularized but asynchronously rotating planet is sketched in Figure 1. The figure emphasizes the diurnal component, that is, the atmospheric variations that undergo one full period per longitudinal circuit of the equator. The gravitational tide couples to the next Fourier harmonic, the semidiurnal tide. This also reaches a temperature maximum in the “afternoon.” To the extent that the atmosphere rearranges itself into approximate lateral pressure equilibrium, density variations are 180° out of phase with temperature variations. For the semidiurnal component, this puts the density maxima in the late morning and evening, i.e. at ±90° of longitude with respect to the temperature maxima. The torque exerted on the thermal tidal density by the gravitational tidal potential tends to accelerate the asynchronous rotation of the atmosphere, as argued by Arras & Socrates (2009).

Gold & Soter (1969) proposed that the thermal tide in Venus’ atmosphere explains why the planet maintains a retrograde rotation despite the fact that the gravitational tide acting on its solid parts would be expected to lead to synchronism in ∼10^8 yr. Their theory was later refined by Ingersoll and Dobrovolskis (Ingersoll & Dobrovolskis 1978, Dobrovolskis & Ingersoll 1980). As these papers make clear, the torque acting on the thermal tide is directly proportional to the longitudinal pressure variation at the planetary surface, which reflects the variation in atmospheric column density by Pascal’s Principle, since the atmosphere can be assumed to be in vertical hydrostatic equilibrium to a good approximation. Venus’ surface can withstand this longitudinal pressure variation because it has elastic strength.

A jovian planet, being gaseous, lacks elastic strength. The excess column density of the colder parts of the atmosphere is counterbalanced—to the degree that hydrostatic equilibrium holds—by an indentation of the convective boundary and a redistribution of the core’s mass toward the hotter longitudes. Insofar as the radial range over which mass redistribution occurs is small compared to the planetary radius, the thermal tide therefore bears no net mass quadrupole. The torque on the atmosphere is opposed by a torque on the upper parts of the convection zone.

This compensation is analogous to geological isostasy: both are applications of Archimedes’ Principle (Watts 2001). The earth’s crust, or lithosphere, floats upon the more plastic aethenosphere, displacing approximately its own weight. Continental crust is less dense than oceanic crust and floats higher, so that column density is ap-
proximately constant. To the extent that isostatic equilibrium holds, therefore, gravitational anomalies experienced by a satellite such as GRACE\[4\] are of second order in crustal density and thickness variations. Whereas terrestrial isostasy operates on such long timescales that rock behaves as fluid, the corresponding timescale for gaseous planets is dynamical, hence less than the tidal period.

Thus, the tidal torque claimed by Arras & Socrates (2009) vanishes to first order in the density variations of the thermal tide. To the next order, the quadrupole moment of the thermal tide aligns with the hottest and most distended parts of the atmosphere, because mass elements are weighted by the squares of their distances from the center. This will lead to a torque of the opposite sign to that of $\Delta\Omega$, hence driving the planet toward synchronous rotation. Similarly, the phase lag of the thermal tide associated with an orbital eccentricity will affect the orbit only to second order, and will tend to circularize the orbit.

Perfect lateral hydrostatic equilibrium cannot exist in atmospheres where the temperature varies along isobars: winds must occur. Furthermore, some mechanical friction or dissipation is required to offset the tendency of the winds to accelerate \footnote{http://www.csr.utexas.edu/grace/} (Goodman 2008). Thus some differential rotation is expected, but not necessarily a thermally driven exchange of angular momentum between rotation and orbit.

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\[\begin{figure}
\centering
\includegraphics[width=\textwidth]{thermal_tide.png}
\caption{Thermal tide. Planetary rotation is nonsynchronous by amount $\Delta\Omega$. Black solid circle is the surface (Venus) or the top of the undisturbed convective core (hot Jupiters). Outermost (red) curve is an isobar: the atmosphere is hottest and most extended in the “afternoon” and coolest before dawn. Lateral pressure gradients concentrate mass (blue arcs) toward colder regions. Innermost (green) circle is an equipotential inside the convection zone (jovian case). This zone being isentropic and hydrostatic, equipotentials coincide with isobars. Hence the mass column above the green circle is constant. Redistribution of the atmosphere is isostatically compensated by shifts in the convective/radiative interface (dashed).}
\end{figure}