Atmospheric tides: modeling and consequences on the rotational dynamics of terrestrial planets

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State of the art

Thermal tides are particularly important for terrestrial planets in the habitable zone where they drive the tidal response of the atmosphere [1]. They play a key role for the equilibrium states of the spin, as in the case of Venus [2] and of exoplanets [e.g. the numerical simulations by 3]. We present here a new analytic approach that generalizes the reference work of Chapman and Lindzen [4] by taking into account radiative processes. The tidal response of the atmosphere, Love numbers and tidal torque are computed explicitly as functions of the tidal frequency and physical parameters, and agree well with results obtained by direct numerical simulations using General Circulation Models (GCM).

Definitions and parameters

System: the atmosphere of an Earth-like planet rotating at the spin frequency $\boldsymbol{\Omega}$, and submitted to a periodical tidal forcing of frequency σ.

Spherical coordinates: radius (r), colatitude (θ), longitude (φ), latitude (δ).

Physical ingredients:
- *Restoring forces* - Coriolis & stratification;
- *Dissipative mechanisms* - Newtonian cooling.

Forcings:
- tidal gravitational potential U,
- thermal insolation power J.

Tidal response:
- variations of pressure (δp), density ($\delta\rho$), temperature (δT), velocity field (V_r, V_θ, V_φ),
- tidal torque $\mathcal{T}$.

Contributions:
- *"Horizontal part"* - direct forcing,
- *"Vertical part"* - related to vertical displacement.

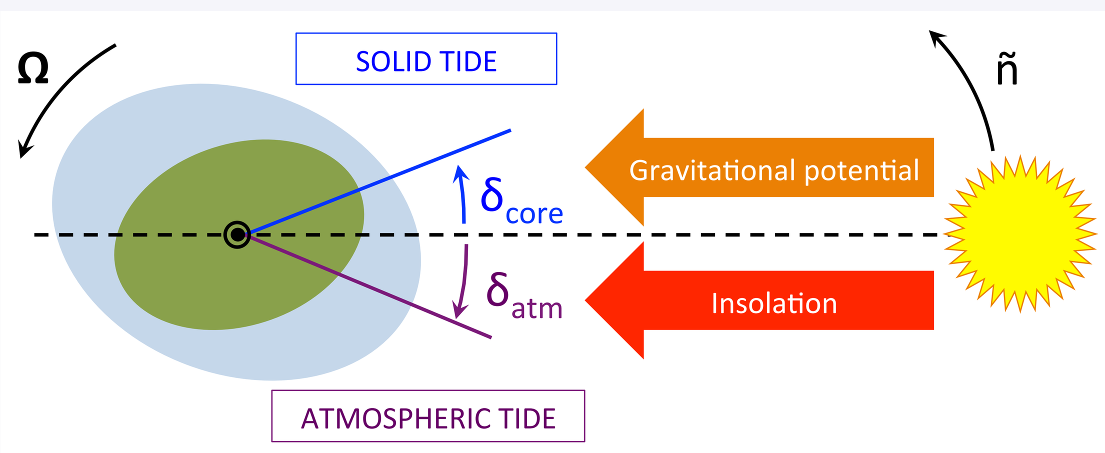

Figure 1: Tidal elongation of a rotating planet composed of a solid core (green) and a gaseous atmosphere (blue), and submitted to gravitational and thermal forcings.

Tidal response of a stably stratified atmosphere

- application of the model to the Solar semidiurnal thermal tide of a Venus-like planet,
- stably stratified isothermal atmosphere in solid rotation with the solid part,
- quadrupolar perturbation $= P_2^2(\cos\theta)\, e^{i(\sigma t + 2\varphi)}$ with academic constant radial profiles,
- tidal frequency given by $\sigma = 2(\Omega - \tilde{n})$, with $\tilde{n}$ the mean motion of the planet.

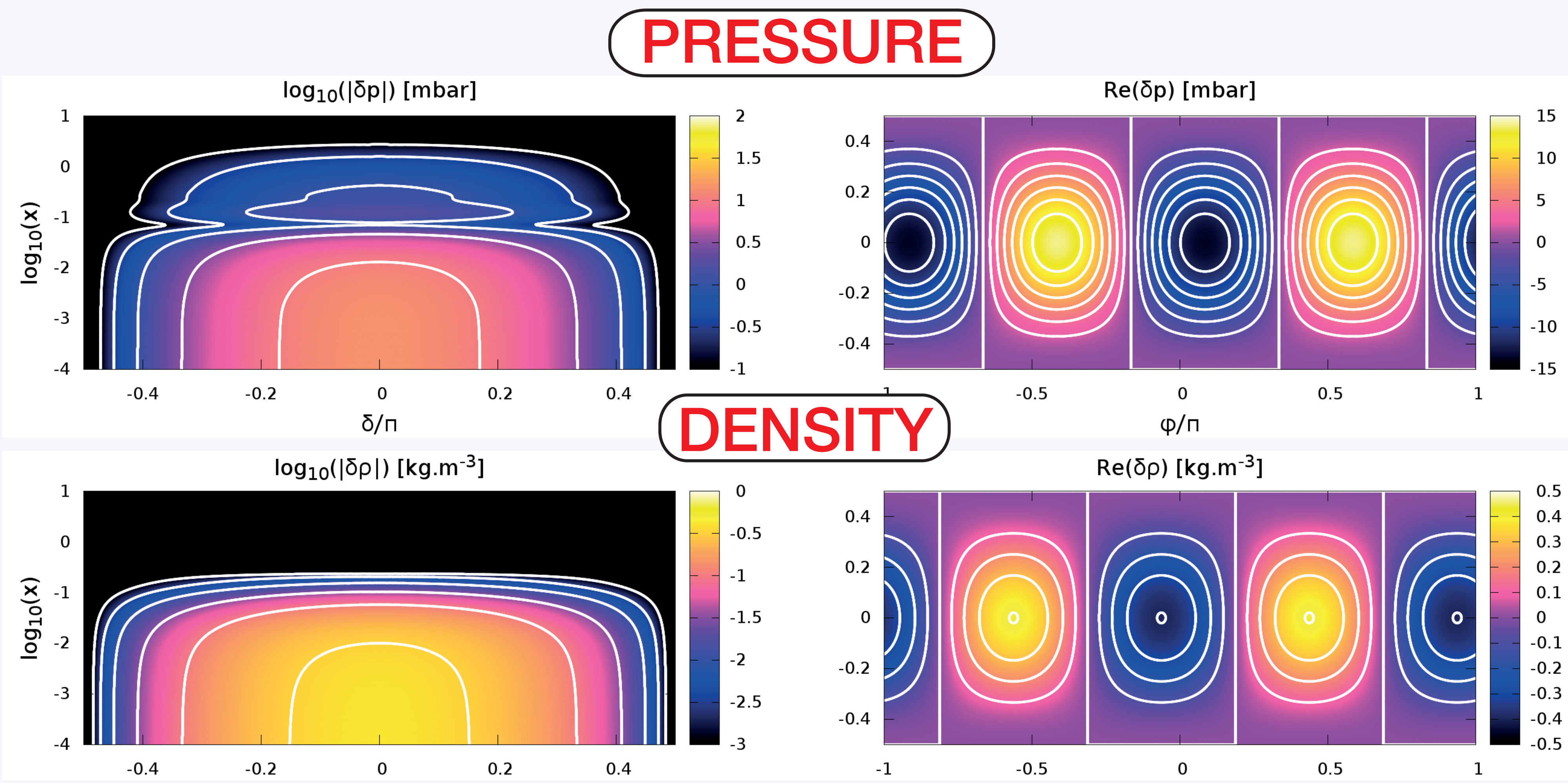

Figure 2: Tidal response of the stably stratified isothermal atmosphere of a Venus-like planet to a quadrupolar thermal forcing. **Left -** Logarithmic amplitudes of pressure (δp) and density ($\delta\rho$) variations as functions of the reduced latitude δ/π and altitude $x = z/H$ (where H is the pressure height scale) in logarithmic scale. **Right -** Real parts of the same quantities expressed at the ground as functions of the reduced longitude φ/π and latitude δ/π.

Tidal torque as a function of the tidal frequency

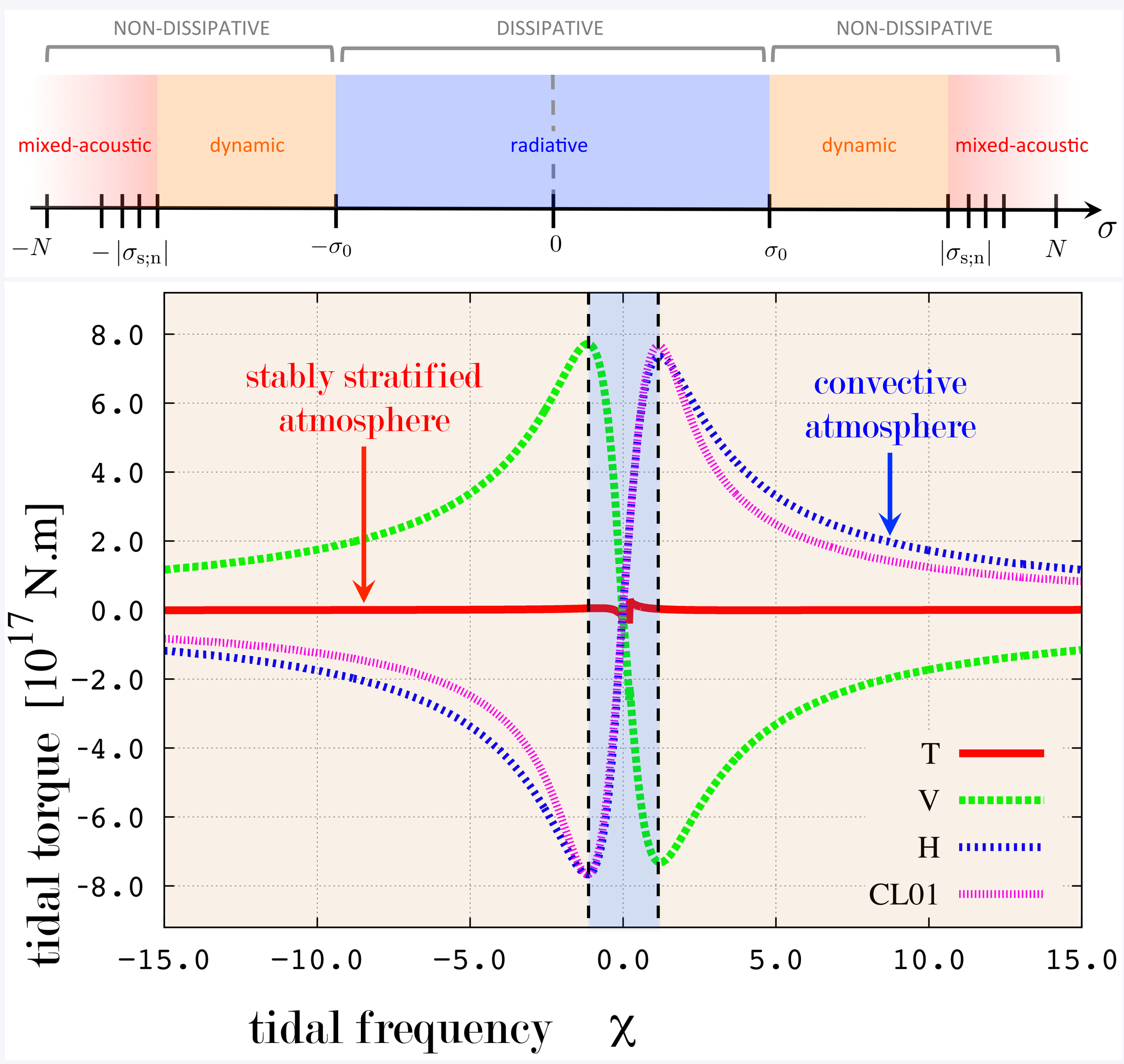

Figure 3: **Top -** Frequency spectrum of the atmospheric tidal response, where N, σ_0 and $\sigma_{s;n}$ are the Brunt-Väisälä frequency, the radiative frequency and the acoustic frequency respectively. **Bottom -** Atmospheric tidal torque induced by Venus' semidiurnal tide as a function of the reduced tidal frequency $\chi = \sigma/(2\tilde{n})$ **in the case where the atmosphere is considered to be isothermal and stably-stratified**. The notations T, H and V designate the **total torque** and its two contributions, the **"Horizontal part"** and the **"Vertical part"**, respectively. The pink curve (CL01) represents the equivalent torque defined by the **empirical model** of [2].

Key points:
- atmospheric tidal torque = function of the tidal frequency,
- stable stratification ⇒ weak torque,
- convection ⇒ strong torque [in agreement with 2, 3],

Consequences on the planet's spin

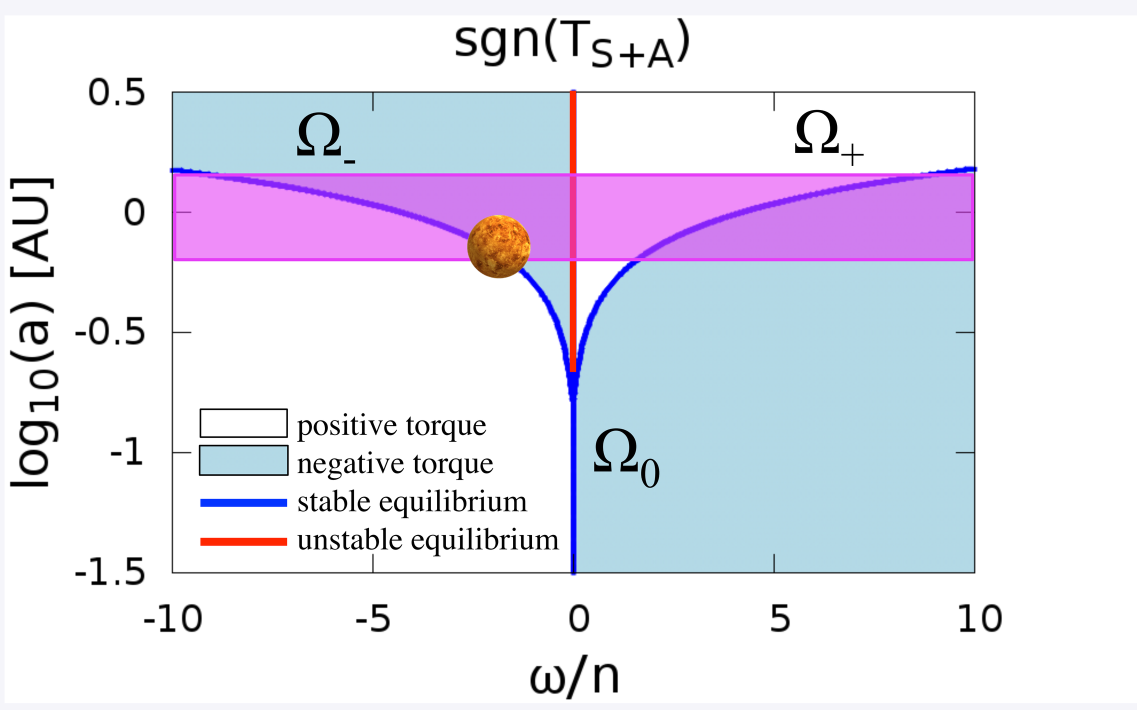

Figure 4: Rotation states of equilibrium of a Venus-like planet as a function of the tidal frequency ω and star-planet distance a in logarithmic scale. Stable (unstable) positions correspond to blue (red) lines. Prograde, retrograde and synchronized states are designated by Ω_+, Ω_- and Ω_0 respectively. The purple region represents the habitable zone.

Key points:
- state of equilibrium = solid and atmospheric torques balance,
- strong thermal tide ⇒ non-synchronized states,
- weak thermal tide ⇒ spin-robit synchronization,

Conclusions and prospects

We have set the bases of a new theoretical framework to study the atmospheric tides of Earth-like planets and exoplanets analytically. It is complementary with numerical simulations. It can be used to explain the qualitative behaviour of an atmosphere submitted to both thermal and gravitational perturbations and to explore the domain of key physical parameters.

References

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