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A rheophysical tidal theory for exoplanets and satellites

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Abstract

Presentation of a new rheophysical theory of the bodily tides of exoplanets and planetary satellites. The basic mechanism is a Newtonian creep of the bodies when submitted to a tidal potential. The theory is applied to determine the pseudo-synchronous rotation of companions and the energy dissipation due to bodily tides. The results are different if the body is “hard”, as terrestrial planets, super-Earths and satellites, or “soft” as giant planets, hot Jupiters or stars.

1. Introduction

During the past century, many versions of Darwin theory were used in the study of the tidal evolution of satellites and planets. Those versions were not exempt of problems, the more important appearing when seeking for solutions near the spin-orbit resonance. All of them show the existence of a stationary solution, which is synchronous when the two bodies move in circular orbits or super-synchronous otherwise (rotational velocity constant and slightly higher than the orbital mean motion). The excess of angular velocity in the stationary rotation when the bodies are in elliptical orbits is physically expected: The torque acting on one body is much larger when it is at the pericenter than in other parts of the relative orbit. Then the angular velocity near the pericenter will enter in time averages with a larger weight and will dominate the result leading to averages larger than the mean motion. Thus, in a planet or satellite moving around its primary in an elliptic orbit, we do not expect the synchronization of the two motions. Tidal theories lead to synchronous stationary solutions only in the circular approximation. One problem of standard Darwin theories is that the average excess of angular velocity of the body is given by $6ne^2$, a quantity independent of the nature of the body. This prediction is, however, not confirmed by the observation of planetary satellites. Titan, for example, should then have a synodical rotation period of about 8.5 years while the radar observations done with the space probe Cassini over several years showed that the present-day rotation period difference from synchronous spin corresponds to a shift of appr. 0.36 degrees per year. Other example is the Moon whose average rotation and orbit are rigorously synchronous notwithstanding an orbital eccentricity 0.055. The only way to conciliate theory and observation is to assume that in all these cases an extra torque able to counterbalance the tidal torque is acting on the body, and the most obvious assumption is the existence of a permanent equatorial asymmetry of the body. This can explain the case of the Moon. But in the cases of Titan and Europa, the situation is more complex. In both cases, we may assume a permanent equatorial asymmetry, but the resulting solution is then an exact synchronization, not a slightly non-synchronous rotation as observed.

2. The theory

This presentation introduces a new rheophysical approach in which the body tends always to creep towards the equilibrium (inviscid) by the only action of the gravitational forces acting on it (self-gravitation and tidal potential) and does it with a rate inversely proportional to its viscosity. The adopted creep law is Newtonian (linear), and at every instant the stress is assumed to be proportional to the distance from the equilibrium. With only one exception, all results of the theory are a direct consequence of the resulting first-order differential equation. The exception occurs when studying the shape of the tide in hard bodies as the Earth and planetary satellites. In these cases, in order to conciliate theory and observation it is necessary to assume that a perfect elastic tide exists, superposed to the creep tide.

3. Results. Synchronization and Energy dissipation.

The results are noteworthy. The first result concerns the problem of the pseudo-synchronous stationary rotation. The excess of rotational velocity is now given by a law that depends on the viscosity of the body. In the “soft” limit, the body behaves like a perfect fluid and the stationary rotation has the same excess given in classical Darwin’s theory. However, in the “hard” limit, as in rocky bodies, the viscosity is too large and, no matter if the eccentricity is large or small, the stationary rotation is close to the true synchronous rotation; the monthly/annual tide (due to eccentricity) does not create the strong torque responsible for the super-synchronicity of fluid bodies. The results for natural satellites are in agreement with the observed values and there is no need of adding a torque due to some “permanent” equatorial asymmetry, which may indeed exist, but is not necessary to counterbalance the tidal torque.

The second result concerns dissipation. In the “soft” limit, the energy dissipation is proportional to the tide frequencyν. This is what happens in giant planets, hot Jupiters and stars. In the “hard” limit, however, the energy dissipation is inversely proportional to the frequency. This is what happens in satellites, terrestrial planets and super-Earths. The maximum dissipation is reached when the tide frequency is equal to a critical frequency inversely proportional to the viscosity of the body.

The dissipation depends on the viscosity and the quality factor Q is not used. In standard theories, the quality factor Q is an ambiguously defined parameter. It is defined using the semi-diurnal tide in the case of a freely rotating body, but using the monthly/annual tide in the case of a pseudo-synchronous companion. In classical applications these two definitions are very distinct and we can handle the two different definitions. However, in the case of high-eccentricity exoplanets, this separation no longer occurs. The dissipation is shared in comparable parts by the semi-diurnal and the monthly/annual tide and we get different values of Q following we consider one tide component or another.

4. Summary and comments

This theory is a new and complete theory of the bodily tide problem, whose results derive from only one physical law: the Newtonian creep. There are no ad hoc lags plugged by hand as in the standard Darwin theory. The way in which creep and elastic tides combine to give rise to geodetic lags increasing when the frequency decreases, for hard bodies, is appealing and may serve as a justification to the theories of Efroimsky and collaborators. In what concerns the discrepancies, it is important to know if they refer to observable phenomena or not. When observational data do not exist, it is impossible to say if the proposed theory is correct or not.

The presented theory is limited to the planar (two-dimensional) problem and does not consider any possible non-linearity of actual creep laws. One positive point to be mentioned is that the theory opens the way for the construction of very complex models and to adopt laws more complete than the Newtonian creep law. Once the basic equations are given, they can be solved numerically. This means that we may adopt physical models as complex as necessary, no matter if their equations can be solved analytically or not.

5. References

[1] Ferraz-Mello, S.: Tidal synchronization of close-in satellites and exoplanets. A rheophysical approach. ArXiv: astro-ph[EP]