The effect of tides on the forced libration of large icy satellites

Tim Van Hoolst[1] and Rose-Marie Baland[2], [1] Royal Observatory of Belgium, Ringlaan 3, B-1180 Brussels, Belgium (e-mail: tim.vanhoolst@oma.be), [2] Université de Nantes, Laboratoire de Planétologie et Géodynamique, 2 chemin de la Houssinière, Nantes, France

Introduction

The gravitational force exerted by a central planet deforms its orbiting moons (tides) and periodically changes their rotation (librations). Tides and librations of large icy satellites rotating synchronously with their orbital motion are usually studied separately but we here show that tides can substantially reduce the libration amplitude of large icy satellites with a subsurface ocean. Moreover, libration also slightly changes the tides. Periodic tides affect libration in two ways: first the periodic tidal bulges modify the gravitational torque exerted by the central planet on the satellite and, secondly, the zonal tides periodically change the polar moment of the satellite, which acts as the inertia for rotational motion. Here we report on a new method developed to study these elastic effects on the longitudinal librations of icy satellites and present numerical results for the largest icy satellites in the solar system: Europa, Ganymede, Callisto, and Titan.

Entirely solid satellites

Without a subsurface ocean, the amplitude of the main longitudinal libration at orbital period depends essentially on the satellite's eccentricity and its equatorial flattening described by the ratio of the equatorial principal moment of inertia difference and the polar moment of inertia [1]. When the effect of tidal deformation is included, the libration amplitude can formally be expressed as for the rigid case by introducing principal moments of inertia modified by deformation. The elastic effects on libration are of the order of 1% for the rocky Europa and about 5 percent for the more icy Ganymede, Callisto, and Titan. Expressed as a shift at the surface of the orientation of the long axis with respect to that for the mean rotation rate, the tidal effect on the libration amplitude is about 1 to 2 meters for those satellites. The effect is small because the satellites' reaction to the periodic tidal forcing, described by the k_2 Love number, is about up to 100 times smaller than the static response, described by the fluid Love number, which is mainly responsible for their aspherical shape. The effect of the gravitational torque on the periodic tidal bulges is about 6 times larger than the effect of zonal tides.

Satellites with a global subsurface liquid

If a subsurface ocean exists as indicated by several observations for the satellites considered, the gravitational torque of the central planet on each internal layer of the satellite forces a libration of these layers, with in general different amplitudes. We calculate how periodic tides change the gravitational torque exerted by the central planet on each of the internal layers of the satellite. Besides external torques, also internal torques between the different layers have to be considered. We here extend the approach that has been developed in [2] and [3], who neglected tidal deformation. In this method internal gravitational torques and ocean pressure torques related to the ellipsoidal form of the layers are taken into account but viscous and electromagnetic torques are neglected.

Since the tidal potential generated by the central planet causes the gravitational potential to change in the global subsurface liquid, the pressure field of the liquid will change too. As a result, a pressure torque will act on the elastic solid layers (the ice shell and the solid interior beneath the ocean). We show that this pressure torque, as for the case of a rigid shell, can formally be expressed as a gravitational torque on the part of the ocean close to the solid layer.

Besides the torques associated with the central planet, also torques between layers have to be considered. Since the static tidal bulges of layers can be oriented differently when the layers rotate differently, an interlayer gravitational torque will arise [2, 3, 4, 5]. In addition, a gravitational torque will exist between the static tidal bulge of a layer and the periodic tidal bulge of another layer and also a torque between the periodic tidal bulges of different layers because all these tidal bulges can be oriented differently. Because the periodic tidal bulges are small compared to the static bulge, the torques between periodic tidal bulges can be neglected and we only retain the gravitational torques between the periodic librational tidal bulge of a layer and the static tidal bulge of another layer. As for the gravitational torque exerted by the central planet, we also include the pressure torques related to the internal gravitational torques.

We calculated the librations of the 4 large icy satellites for an extended set of possible interior strucures compatible with current observational constraints. The libration amplitudes are much larger than for entirely solid layers, but with respect to rigid solid layers the amplitude of libration of the shell is reduced by values up to 54% for Europa, 31% for Ganymede, 35% for Callisto, and 34% for Titan due to the elastic effects. For example, for an entirely solid Titan, the libration amplitude is about 50 meters. With subsurface ocean, it increases to values larger than 1 km for thin ice shells.

Besides gravitationally forced librations, seasonal variations in the atmosphere of Titan also cause the rotation of Titan to change on a seasonal timescale. We show that tidal elastic effects increase the amplitude of these long-term variations in the rotation rate by up to about 30%.

Acknowledgments

This work was financially supported by the Belgian PRODEX program managed by the European Space Agency in collaboration with the Belgian Federal Science Policy Office. R.M.B. is funded by the Conseil Régional des Pays de la Loire, France.

References

[1] Comstock, R.L., Bills, B.G. 2003. J. Geophys. Res. 108(E9), 5100, doi:10.1029/2003JE00210
[2] Van Hoolst T., Rambaux N., Karatekin Ö., Baland R.-M., 2009. Icarus 200, 256-264
[3] Baland, R.-M., Van Hoolst, T., 2010. Icarus 209, 651-664
[4] Xu, S., Crossley, D., Szeto, A.M.K., 2000. Phys. Earth Planet. Int. 117, 95110
[5] Dumberry, M., 2008. Geophys. J. Int. 172, 903-920