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Rhea: a reorientation event detected from gravity measurements of the spacecraft Cassini

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Abstract

On 26th November 2005 Cassini spacecraft encountered Saturn's satellite Rhea in a flyby devoted to gravity science. Several analyses of the radio-metric data (range and range rate) obtained during the encounter have been published, all of them aiming to determine the mass and the quadrupole gravity field of the satellite. We present here a new analysis where the effects of the gravity anomaly produced by Tirawa impact basin on the gravity field estimate are accounted for. By comparing the gravity field of the pure quadrupole with the one derived by fitting the quadrupole and the gravity anomaly, we estimate also the reorientation of the inertia ellipsoid caused by the mass redistribution occurred after the impact. The analysis shows that the gravity field estimate is significantly affected by the Tirawa basin, and that the quadrupole gravity field moves toward values closer to the ones expected for a relaxed body.

1. Introduction

On 26th November 2005 Cassini flew by Rhea at a closest approach altitude of 500 km, providing the first precise determination of the satellite's mass and quadrupole gravity field. The knowledge of the gravity field is crucial for any inference on the interior structure of a celestial body. For a synchronously rotating body in hydrostatic equilibrium, the relation between gravity coefficients J_2 and C_{22} is predicted to fulfil the relation $3J_2=10C_{22}$ (Zharkov et al.(1985)). The knowledge of the degree 2 Stokes coefficients can be used to infer whether a body is in hydrostatic equilibrium. If this is the case, the Radau-Darwin equation provides the moment of inertia (MoI) of the body, a quantity of paramount importance for the construction of geophysical models of the interior structure. The Cassini data, obtained by tracking the spacecraft through the closest approach (C/A) of Rhea, were subject to three independent analyses. Mackenzie et al. (2007) for the Cassini Navigation Team (NAV) and Iess et al. (2007) for the Cassini Radio Science Team (RS) have obtained independent and compatible results, without any a priori assumption about the hydrostatic equilibrium. Anderson and Schubert (2007) used a hydrostatically constrained solution for geophysical interpretation. Subsequently a new analysis, combining the Radio Science and NAV approaches (Mackenzie et al.(2008)) confirmed that a reliable gravity field estimate is obtained without the need of the hydrostatic constraint. This analysis shows that Rhea's quadrupole field is partly non-hydrostatic. However Mackenzie et al.(2008) suggested that a mechanism that can produce a non-hydrostatic gravity field is the formation of impact basins after the completion of the satellite's thermal evolution. A huge impact and the following mass redistribution could have changed the orientation of the principal axes of inertia. The presence of numerous craters on Rhea's surface suggests the investigation of this hypothesis. The analysis we present here aims to evaluate the effect of a gravity anomaly produced by large Tirawa's impact basin on the estimate of the gravity field. This basin has specific characteristics suggesting an influence on the gravity field estimate: 1) its position on the surface of Rhea is very close to Cassini's ground-track at C/A, and 2) its diameter (approximately 320 km) is quite large. The gravity field estimate was carried out using radiometric range rate observables obtained by means of a coherent radio link between the spacecraft and the antennas of the Deep Space Network (DSN). The orbital fit included the quadrupole coefficients and a mass anomaly located at the center of the Tirawa basin.

2. Tirawa impact basin

The mass redistribution resulting from a large impact would change the orientation of the principal axes of inertia. After an appropriate time, internal dissipation will force a reorientation of the principal axes. In order to reach a state of minimum energy, this reorientation will end up with the new (post-impact) axis of least moment of inertia pointing toward the empty focus of the orbit. If the crust of the satellite is sufficiently rigid, the permanent, pre-impact tidal bulge changes its initial orientation and no longer points toward the empty focus. The orbit determination software uses a body-fixed reference frame, which almost coincides with the orbital reference frame. Therefore the reorientation will affect the estimates of J_2 and C_{22}, likely leading to a non-hydrostatic value of the J_2/C_{22} ratio. In order to evaluate the influence of the Tirawa basin on the estimate of the quadrupole gravity field we include a negative, point-like gravity anomaly in the dynamical model used in the orbital fit. Its location coincides with the center of Tirawa. Under the assumption of a rigid crust, we are essentially estimating the pre-impact quadrupole field. In our analysis we did not account for a possible isostatic rebound. Isostatic compensation would reduce the effect of Tirawa on the gravity field estimation.

3. Reorientation

Determination of inertia axes reorientation angle is carried out using MacCullagh formula

$$\left(\mathbf{Q} = \frac{1}{3}\mathbf{1}Tr(\mathbf{I}) - \mathbf{I}\right) \tag{1}$$

that relates the moments of inertia to the second degree gravity coefficients. As the quadrupole tensor **Q** and inertia tensor **I** share the same eigenvectors the orientation of inertia principal axes can be easily determined by diagonalizing the measured quadrupole tensor. The orientation of the pre-impact principal axes is given by the eigenvectors of the quadrupole tensor, whose elements are the estimated pre-impact gravity field coefficients. The complete quadrupole tensor determined with estimated J_2, C_{22}, S_{22} and Tirawa's negative mascon provides the new, post-impact principal axes. Assuming that the effect of the impact is a rotation of inertia axes only in the orbital plane, the reorientation angle is simply determined by the difference between the two set of inertia axes previously found.

4. Conclusions

The analysis shows that the estimate of the quadrupole field is significantly influenced by the presence of Tirawa. Increasing the missing mass associated to the Tirawa basin, the estimated quadrupole field shifts towards more hydrostatic values. However equilibrium is never reached, even for the maximum value of the missing mass compatible with the images of the Cassini's camera. Our results confirm the hypothesis that after the impact Rhea underwent a reorientation. Its magnitude is estimated in the range of 1-2 degrees, depending almost linearly on the mass deficiency associated to the basin.

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