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Rhea gravity field and interior modeling from Cassini data analysis

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ABSTRACT

During its tour of the Saturn system, Cassini performed two close flybys of Rhea dedicated to gravity investigations, the first in November 2005 and the second in March 2013. This paper presents an estimation of Rhea's fully unconstrained quadrupole gravity field obtained from a joint multi-arc analysis of the two Cassini flybys.

Our best estimates of the main gravity quadrupole unnormalized coefficients are $J_2 \times 10^6 = 946.0 \pm 13.9$, $C_{22} \times 10^6 = 242.1 \pm 4.0$ (uncertainties are 1-σ). Their resulting ratio is $J_2/C_{22} = 3.91 \pm 0.10$, statistically not compatible (at a 5-σ level) with the theoretical value of 10/3, predicted for a hydrostatic satellite in slow, synchronous rotation around a planet. Therefore, it is not possible to infer the moment of inertia factor directly using the Radau–Darwin approximation.

The observed excess J_2 (gravity oblateness) was investigated using a combined analysis of gravity and topography, under different plausible geophysical assumptions. The observed gravity is consistent with that generated by the observed shape for an undifferentiated (uniform density) body. However, because the surface is more likely to be water ice, a two-layer model may be a better approximation. In this case, and assuming a mantle density of 920 kg/m^3, some 1–3 km of excess core oblateness is consistent with the observed gravity. A wide range of moments of inertia is allowed, but models with low moments of inertia (i.e., more differentiation) require greater magnitudes of excess core topography to satisfy the observations.

1. Introduction

Discovered on December 23, 1672 by Giovanni Domenico Cassini, Rhea is the second largest moon of Saturn, with a mean radius of about 764 km.

Before Cassini's arrival in the Saturn system, only the gravitational parameter GM was known from the analysis of *Pioneer* and *Voyager* data (Campbell and Anderson, 1989). Using this and the estimated volume (from camera images), a bulk density of about 1200 kg/m^3 was derived, relatively small and compatible with a mixture of about 75% by mass water ice (density 1000 kg/m^3) and 25% rock-metal (density 3000 kg/m^3).

During its mission in the Saturn system, Cassini performed four close encounters of Rhea, of which only two were devoted to gravity investigations. The first gravity flyby, referred to as R1, according to the numbering scheme used by the *Cassini* project, was performed on November 26, 2005, during the main mission, and the second and last gravity flyby, referred to as R4, was performed on March 9, 2013, during the Solstice mission. The main orbital and geometrical characteristics of R1 and R4 are summarized in Table 1, while Fig. 1 displays the ground track of the flybys, for a time interval of about ±2 h around the closest approach (black circles).

Radiometric data acquired during the first encounter (R1) were used to estimate the gravity field of Rhea. A first estimate (Anderson and Schubert, 2007) was obtained under the assumption of hydrostatic equilibrium, i.e. constraining the unnormalized gravity coefficients J_2 and C_{22} to a ratio of 10/3. From this estimation, by applying the Radau–Darwin relation the authors obtained a normalized moment of inertia of about 0.3911 ± 0.0045 (a value of 0.4 would imply a constant density interior). The authors concluded that the satellite's interior is a homogeneous, undifferentiated mixture of ice and rock, with possibly some compression of the ice and transition from ice I to ice II at depth.

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Table 1
Main geometrical and orbital characteristics of R1 and R4 gravity fybys.

Values at C/A	Unit	R1	R4
Epoch	(UTC)	26-NOV-2005, 23:50	09-MAR-2013, 19:40
Altitude	(km)	502	999
Relative velocity	(km/s)	7.3	9.3
Inclination	(°)	17	106
Latitude	(°N)	−10.2	18.8
Longitude	(°E)	−91.5	−176.2
Normal-to-Earth angle	(°)	106	117
Sun–Earth–Probe angle	(°)	113	128

In parallel, the radiometric data acquired during R1 were independently analyzed by the *Cassini* Navigation team (Mackenzie et al., 2007) and by the Cassini Radio Science team (Iess et al., 2007). Both analyses estimated the moon's GM and quadrupole gravity coefficients J_2 and C_{22}, obtaining different solutions, but consistent at the 2σ level, as a result of different analysis approaches. The two approaches were then combined to obtain a joint "best" unconstrained estimation of the quadrupole field (Mackenzie et al., 2008). The solution obtained is not statistically compatible with hydrostatic equilibrium, hence no useful constraint on Rhea's interior structure could be imposed. Hydrostatic equilibrium was also ruled out by applying this constraint to the estimated quadrupole field coefficients, and this led to a significant degradation of the orbital fit at closest approach. To explain the non-hydrostatic ratio J_2/C_{22}, the authors theorized that a large collision occurred after the completion of the thermal evolution of the satellite, causing a redistribution of mass and a reorientation of the tidal bulge.

More recently Anderson and Schubert (2010) stated that the differences in the previously published gravity fields are probably caused by a mis-modeling of the non-gravitational acceleration acting on *Cassini* caused by anisotropic thermal emission. To avoid this issue, these authors restricted the analysis to a subset of data around the closest approach (±2000 s), where "the information from Rhea's quadrupole gravitational field is confined". They obtained a new solution in agreement with Anderson and Schubert (2007), using the hypothesis of hydrostatic equilibrium. Moreover, these authors concluded that non-hydrostaticity is not supported by the data.

The different estimations of J_2 and C_{22} published to date are shown in Fig. 2. To resolve these discrepancies, a second and final gravity flyby was planned in *Cassini*'s Solstice. No other flybys of Rhea are scheduled in the *Cassini* mission. R1 was characterized by a very low inclination, about 17° at the closest approach (C/A), in order to de-correlate the estimation of J_2 and C_{22}, while R4 was designed to be nearly polar, with a high inclination at C/A, about 106°. However, the C/A of R4 was about 999 km, twice as high as R1 (about 502 km), thus significantly reducing the information content about Rhea's quadrupole gravity field in this second flyby. The Sun–Earth–Probe (SEP) angle was larger than 110° during both encounters, thus range-rate measurements were only slightly affected by the harmful effect of solar plasma.

This paper is organized as follows: Section 2 describes the data analysis approach for the estimation of Rhea's gravity field, along with the spacecraft dynamical model, and the data selection and calibration procedure. Section 3 provides a geophysical interpretation of the results, by means of a combined analysis of Rhea's estimated gravity and topography. Finally Section 4 summarizes our findings and conclusions.

2. Gravity analysis

2.1. Introduction

The determination of the gravity field of a celestial body plays a crucial role in the investigation of its internal composition, structure and evolution, because it provides one of the very few direct measurements of its internal mass distribution, even if the inversion process is not unique.

The gravity field of Rhea was precisely determined by reconstructing the trajectory of *Cassini* during the two close encounters of the satellite. The main observable quantity used in the gravity estimation was the spacecraft range-rate, obtained from the frequency shift due to the relativistic Doppler effect, averaged over a count time of 60 s, of a highly stable microwave carrier transmitted from an Earth ground station to the spacecraft, that coherently retransmits the signal to Earth by means of a precise transponder.

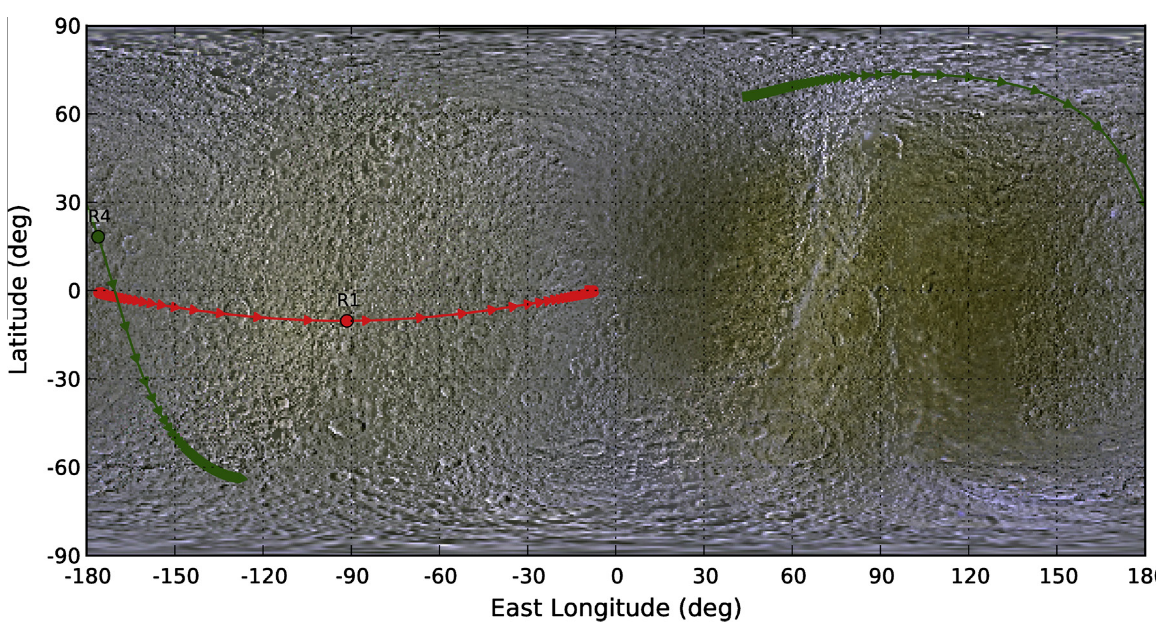

Fig. 1. Cassini ground track on Rhea during R1 and R4, considering a time interval of ±2 h around the closest approach.