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Iapetus' near surface thermal emission modeled and constrained using Cassini RADAR Radiometer microwave observations

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ABSTRACT

Since its arrival at Saturn, the Cassini spacecraft has had only a few opportunities to observe Iapetus, Saturn's most distant regular satellite. These observations were all made from long ranges (>100,000 km) except on September 10, 2007, during Cassini orbit 49, when the spacecraft encountered the two-toned moon during its closest flyby so far. In this pass it collected spatially resolved data on the object's leading side, mainly over the equatorial dark terrains of Cassini Regio (CR). In this paper, we examine the radiometry data acquired by the Cassini RADAR during both this close-targeted flyby (referred to as IA49-3) and the distant Iapetus observations. In the RADAR's passive mode, the receiver functions as a radiometer to record the thermal emission from planetary surfaces at a wavelength of 2.2-cm. On the cold icy surfaces of Saturn's moons, the measured brightness temperatures depend both on the microwave emissivity and the physical temperature profile below the surface down to a depth that is likely to be tens of centimeters or even a few meters. Combined with the concurrent active data, passive measurements can shed light on the composition, structure and thermal properties of planetary regoliths and thus on the processes from which they have formed and evolved. The model we propose for Iapetus' microwave thermal emission is fitted to the IA49-3 observations and reveals that the thermal inertias sensed by the Cassini Radiometer over both CR and the bright mid-to-high latitude terrains, namely Ronceveaux Terra (RT) in the North and Saragossa Terra (ST) in the South, significantly exceed those measured by Cassini's CIRS (Composite Infrared Spectrometer), which is sensitive to much smaller depths, generally the first few millimeters of the surface. This implies that the subsurface of Iapetus sensed at 2.2-cm wavelength is more consolidated than the uppermost layers of the surface. In the case of CR, a thermal inertia of at least 50 $J\,m^{-2}\,K^{-1}\,s^{-1/2}$, and most probably >200 $J\,m^{-2}\,K^{-1}\,s^{-1/2}$ is inferred. This suggests a gradient in density with depth or, more likely, that the Radiometer has probed the icy substrate underlying the dark layer. Furthermore, the measured thermal emission is found to arise from the upper few meters of the subsurface, which points to tholins, rather than iron oxide compounds, as the primary contaminants of the dark material. We also find that, although there is a latitudinal decrease probably related to the thinning of the dark layer away from the Equator, the CR region exhibits a high 2.2-cm emissivity, 0.87 in average, which is close to the emissivity of Phoebe, a putative source of the dark matter. In the case of RT + ST, model fitting points to a mean thermal inertia of $\sim$160 $J\,m^{-2}\,K^{-1}\,s^{-1/2}$ along with the possible presence of an absorbing compound in the regolith of the bright terrains. Nevertheless, this layer is transparent enough for the Radiometer to capture the seasonal contrast between the northern and southern hemispheres. Lastly, a global decline of the microwave emissivity with latitude is revealed; it is probably indicative of a progressive increase of the water ice content in the near surface.

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1. Introduction

Iapetus, the third largest satellite of Saturn, is well known for its dramatic and unique albedo dichotomy (Cassini, 1677). Optical images from the Voyager and Cassini spacecraft have shown that its trailing hemisphere (centered on 270°W) and poles are about an order of magnitude brighter than most of its leading hemisphere (centered on 90°W) (Squyres et al., 1984; Porco et al., 2005). The origin of this two-tone coloration has long been controversial but there seems to be now a consensus toward an exogenic deposition of low-albedo material on the leading side of the icy moon. The exogenous dark material most probably originated in the region of the irregular Saturnian satellites and in particular Phoebe, or the vast debris ring from Phoebe, that crosses Iapetus' orbit (e.g. Soter, 1974; Cruikshank et al., 1983; Buratti et al., 2002; Verbiscer et al., 2009; Tosi et al., 2010; Dalle Ore et al., 2012). It has also been proposed that the darkening of the leading hemisphere is enhanced by the thermal segregation of water ice leaving behind a darker remnant material in the relatively warm equatorial region (Spencer and Denk, 2010).

Iapetus' low density ($\sim$1.1 g cm^{-3}) implies that its bulk composition is dominated by water ice (Rappaport et al., 2005; Thomas, 2010). Cassini Visual and Infrared spectrometer's (VIMS) observations of Iapetus' bright terrains in the spectral range 0.35–5.1 μm indeed strongly point to the dominance of water ice (Buratti et al., 2005; Clark et al., 2012), similar to other icy Saturnian satellites. However, infrared (IR) spectra have revealed that the dark terrains of Iapetus are most probably coated with a mixture of carbon-rich material, metallic iron, iron oxide (hematite Fe_2O_3), and still-unidentified compounds (Buratti et al., 2005; Cruikshank et al., 2008; Clark et al., 2012; Dalle Ore et al., 2012).

Iapetus' surface has also been observed in the microwave domain by ground-based radars and by the RADAR onboard the Cassini satellite. In an active mode, radar measurements of icy surfaces are mostly sensitive to the ice purity and the structure of the near surface. In a passive mode, i.e. as a radiometer, it records the microwave thermal emission from the top layers of the regolith. In both cases, the instrument typically senses depths of between 10 and 100 wavelengths on most icy materials and can thus provide unique insight into depths much greater than the ones sensed by IR thermal spectrometers.

Ground-based observations of Iapetus' leading and trailing sides from the Arecibo 12.6-cm radar system show no hemispheric asymmetry (Black et al., 2004) while distant Cassini RADAR observations of the moon at a wavelength of 2.2-cm mirror the optical albedo dichotomy. The electrical skin depth being proportional to the wavelength, this suggests that the thickness of the dark layer is at least a few decimeters but probably does not exceed one meter (Ostro et al., 2006, 2010). This would be consistent with the deposition of an exogenic layer of a few tens of cm predicted by Verbiscer et al. (2009) or Tamayo et al. (2011), but also with the mechanism of thermal migration of water ice proposed by Spencer and Denk (2010). On the other hand, the lack of detection of a hemispheric asymmetry and the low radar albedos recorded at 12.6 cm could instead be indicative of the increasing presence of an absorbing contaminant with depth (Ostro et al., 2006, 2010) and thus does not necessary place an upper limit on the thickness of the dark layer.

As a general matter, moderately low radar echoes (relative to other Saturnian and Galilean icy satellites) were recorded over Iapetus from long-range (Ostro et al., 2006). Consistently, the concurrent Cassini distant passive radiometry observations revealed that the 2.2-cm emissivity of Iapetus' surface (i.e. its ability to emit energy by radiation at this wavelength) is, with Phoebe and Callisto, among the highest ever measured on an airless icy satellite (Ostro et al., 2006). In this paper, we explore more recent distant radiometry observations of Iapetus and reduce the old and new datasets using the up-to-date calibration of the Cassini Radiometer (Janssen et al., 2013). We also examine the only available dataset of spatially resolved radiometry observation of Iapetus.

Because of its large distance from Saturn and its high obliquity, Iapetus is dynamically difficult to reach and the Cassini orbital tour could only permit one close encounter, with an altitude <20,000 km at closest approach, during Cassini orbit 49 on September 10, 2007. Spatially resolved data were acquired during the third sequence of this flyby in SAR (Synthetic Radar Aperture), scatterometry, and radiometry modes over much of the leading side of the moon. These data are hereafter referred to as IA49-3 data. The obtained SAR image is described in Ostro et al. (2010) while the scatterometry data were processed and analyzed by Wye (2011). In this paper, we focus on the radiometry data. We will nevertheless use and recall the results of the scatterometry analysis.

Cassini radiometry observations contain information about the crustal layers of Iapetus. In particular, they can help to constrain thermal and electrical properties of the subsurface to the depth sensed by the instrument (eventually found to be of the order of few meters) thus providing clues on the physical state and composition of the dark and bright terrains of the Saturn's moon. In Section 2, we describe the distant and IA49-3 close-targeted observations of Iapetus. Section 3 presents the model we have developed in order to reproduce Iapetus' microwave thermal emission. This model is adapted to the IA49-3 observational conditions in Section 4 before being compared to the data in Section 5. This comparison leads to new constraints for Iapetus' dark and bright terrain regolith properties, the implications for which are also discussed in Section 5. The findings of this paper shed light on the processes from which Iapetus has formed and evolved.

2. Cassini microwave radiometry observations of Iapetus

Though the Cassini RADAR was initially designed to observe the surface of Titan through the veil of its optically-obscuring atmosphere Elachi et al., (2004), the instrument is occasionally used to examine other Saturn moons from long ranges (between 50,000 km and 500,000 km, see Ostro et al., 2006, 2010) or, less frequently, during close dedicated flybys. In Iapetus' case, the Cassini RADAR has had only three opportunities for observation: very early in the mission, even before Huygens landed (flyby IA01, December 31, 2004–January 1, 2005), during the 17th orbit of Cassini around Saturn (flyby IA17, November 17, 2005) and around the previously-mentioned close encounter on the 49th orbit (flyby IA49, September 9–10, 2007). In this section, we report on the data acquired in the passive radiometry mode of the instrument during these three flybys.

2.1. IA01, IA17 and IA49 distant radiometry observations of Iapetus

Typical distant Cassini RADAR observations of Saturn's moons occur at ranges exceeding 50,000 km where the antenna beamwidth is comparable to or greater than the apparent angular extent of the target's disk. These experiments are designed for disk-integrated albedo and average temperature calculation.

Most of the distant radiometry observations of Titan performed during Cassini's prime mission are summarized in Janssen et al. (2009), while Ostro et al. (2006) report on the disk-averaged brightness temperatures of Saturn's major airless satellites measured at the beginning of the mission. Here, we pursue this work for Iapetus, adding more recent measurements and using the current calibration of the Radiometer. This calibration is based on