



Cassini's geological and compositional view of Tethys



Katrin Stephan^{a,*}, Roland Wagner^a, Ralf Jaumann^{a,b}, Roger N. Clark^c, Dale P. Cruikshank^d, Robert H. Brown^e, Bernd Giese^a, Thomas Roatsch^a, Gianrico Filacchione^f, Dennis Matson^g, Cristina Dalle Ore^d, Fabrizio Capaccioni^f, Kevin H. Baines^h, Sebastien Rodriguezⁱ, Norbert Krupp^j, Bonnie J. Buratti^f, Phil D. Nicholson^k

^aDLR, Institute of Planetary Research, 12489 Berlin, Germany

^bDept. of Earth Sciences, Inst. of Geosciences, Free University, Berlin, Germany

^cU.S. Geological Survey, Denver Federal Center, Denver, CO 80225, USA

^dNASA Ames Research Center, Moffett Field, CA 94035, USA

^eLunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA

^fINAF-IAPS, 00133 Rome, Italy

^gJet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

^hSpace Science and Engineering Center, University of Wisconsin-Madison, Madison, WI 53706, USA

ⁱLaboratoire AIM, Université Paris Diderot – Paris 7/CNRS/CEA-Saclay, DSM/IRFU/SAp, 91191 Gif sur Yvette, France

^jMax-Planck-Institut für Sonnensystemforschung, 37077 Göttingen, Germany

^kDepartment of Astronomy, Cornell University, Ithaca, NY 14853, USA

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ABSTRACT

The Saturnian satellite Tethys exhibits geological and spectral properties, whose appearance, nature and spatial distribution partly mirror those identified on the neighboring satellites Dione and Rhea or fit to the picture how spectral surface properties are expected to change from one satellite to the other within the inner Saturnian system. However, we also identified spectral variations that are unique in the Saturnian system. Whereas geologically young surface features are characterized by pure H₂O–ice composition with relatively large particles, which match the particle sizes measured for fresh surface features also on Dione and Rhea, geologically old weathered regions are dominated by submicron-sized ice particles. Our investigations confirm that the Odysseus impact event did not cause the formation of Tethys' extended graben system Ithaca Chasma. On the contrary, Odysseus might be responsible for the N–S trending 'icy' bands that mark Tethys' surface in the center of its leading and trailing hemisphere.

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1. Introduction

Since 2004 Cassini has been orbiting the Saturnian system with its instruments detecting the chemical and physical properties of Saturn's atmosphere, magnetosphere, satellites, and rings. The VIMS instrument is the first imaging spectrometer that operates in the Saturnian system, enabling not only the identification of the surface composition but also the mapping of its distribution on the surfaces of Saturn's satellites. Spectral analyses of Dione, Rhea, Iapetus, Hyperion (Clark et al., 2008; Clark et al., 2012; Cruikshank et al., 2007; Stephan et al., 2010; Stephan et al., 2012) and Enceladus (Jaumann et al., 2008) have made it possible to relate location and extension of spectral units to specific geological and/or geomorphological surface features or characteristics of the

space environment—which is essential to resolve the origin of the surface compounds and thus provides valuable information to describe the evolution of the satellite. Although the VIMS spectra of the icy satellites' surfaces are mostly dominated by H₂O–ice, its distribution and physical characteristics differ distinctly from one satellite to the other (Clark et al., 2008; Clark et al., 2012; Jaumann et al., 2008; Stephan et al., 2010; Stephan et al., 2012). Global hemispherical differences are mostly related to the satellite's position in the Saturnian system, i.e., the distance to Saturn and/or its E ring, with particles trapped in Saturn's magnetosphere and/or ice grains of the E ring impacting their surfaces (Clark et al., 2008; Stephan et al., 2010; Stephan et al., 2012). Thanks to VIMS mapping capabilities, compositional variations on a regional and local scale can be identified and related to the surface geology. In particular, young or reactivated impact craters and tectonic features—revealing “fresh” (unaltered) surface material—offer a unique view into the crustal properties of the satellite (Stephan et al., 2010; Stephan et al., 2012). Furthermore, the comparison of the physical and chemical surface

* Corresponding author. Tel.: +493067055422.

E-mail address: Katrin.Steph@dlr.de (K. Stephan).

properties of impact craters emplaced at different times enables to study the alteration of the surface material due to space weathering processes.

In this paper we present the analysis of the spectral properties of Tethys in comparison to its geology, which is unique in several ways and completes our investigation of Saturn's inner major satellites. Tethys is 1062 km in diameter and exhibits a very low density ($\sim 0.985 \text{ g/cm}^3$) (Thomas, 2010) suggesting that the satellite is composed almost entirely of H_2O -ice plus a small amount of rock.

Tethys is marked by the huge impact basin Odysseus, which is expected to have globally affected surface and internal properties. Odysseus is still discussed as being responsible for the formation of Tethys' prominent tectonic system, Ithaca Chasma (Moore and Ahern, 1983; Moore et al., 2004). Surface ages, however, indicate that Ithaca Chasma is geologically older than Odysseus (Giese et al., 2007)—speaking against this relationship. Further, the impact crater statistics, at the basis of Tethys' surface age calculations, are unusual. The distribution of small impact craters (1 to 10 km in diameter) is distinctly different from the other Saturnian satellites because the number of these small impact craters is much higher relative to the larger ones (Schmedemann et al., 2014).

Finally Tethys has a high albedo value of about 0.8 in the visual spectral range (Verbiscer et al., 2007) indicating a composition largely made of H_2O -ice. Possibly, the high reflectivity is enhanced because Tethys collects Saturn's E-ring H_2O -ice particles generated by geysers on Enceladus. Tethys orbits Saturn at a distance of 294,660 kilometers, between the orbits of Enceladus and Dione, and is thus embedded in the E ring environment. Consequently, the comparison of the compositional aspects of all Saturnian satellites provides valuable information for the evolution of the Saturnian system.

Key questions about Tethys upon which this investigation is focused to unravel include:

1. How are Odysseus and Ithaca Chasma spectrally characterized? How are they related to each other in general? Do the spectral surface properties provide any hint of a common origin and their relation to the history and formation of the body?
2. Are there any fresh impact craters on Tethys? What are the similarities and differences in the spectral properties of fresh surface features on Tethys compared to fresh impact craters on Dione (Creusa) and Rhea (Inktoni)?
3. What are the differences in spectral properties between any fresh surface material and the surroundings? What are the resurfacing dynamics and space weathering effects of the satellite?
4. Are there any hemispherical changes in the spectral properties similar to Dione and Rhea related to the interaction with Saturn's magnetosphere? How do they change from one satellite to the other? What information do they give about the properties of Saturn's magnetosphere?
5. How do the E ring particles interact with Tethys, which orbits relatively close to the E ring?

We start the presentation of our work with an overview of the data set we used (Section 2), including the methods used for the spectral and geological analysis. Sections 3 and 4 present the achieved results. In Section 3 the identified major geological units are described in detail. In Section 4 Tethys spectral properties and the distribution of spectrally different units across Tethys' surface as well as their possible associations to specific geological—and/or geomorphological features or location on Tethys's surface are discussed. The possible implications for the origin/formation of Tethys' surface compounds and Tethys' geological evolution are discussed in Section 5 and summarized in Section 6.

2. Cassini data basis

Since 2004, the Cassini spacecraft has been orbiting the Saturnian system exploring Saturn, its magnetosphere and its satellites with numerous flybys at Tethys (Tab. 1). Cassini performed 10 (1 targeted and 9 non-targeted) flybys during its nominal mission until 2008, with an altitude between 1500 and about 120,000 km. In particular, Cassini's orbit 47 offered the unique possibility to observe Ithaca Chasma, Tethys' most prominent tectonic features (see below) from a distance of only 16,000 km. Throughout the first extended mission, the Cassini Equinox Mission, from 2009 and 2010, more data were collected during 11 flybys with a closest approach of about 37,000 km during orbit 136, which mainly observed Tethys' trailing hemisphere. In the current second extended mission, the Cassini Solstice Mission, which will continue until 2017, already 7 flybys within distances between about 7600 and 69,000 km were successfully performed so far, with orbit 168 offering the possibility to investigate Tethys' largest impact crater Odysseus.

2.1. ISS observations

Spatially highly resolved clear filter images acquired by the Imaging Science Subsystem (ISS) provided not only the geological context but provided the possibility to associate any changes in the spectral properties to specific geographic location, as well as individual geological and/or geomorphological surface features.

A digital global mosaic in a simple-cylindrical map-projection of Tethys produced with clear filter images of the Cassini ISS instrument with a map scale of 0.29 km/pixel, as presented in Roatsch et al. (2009), was used for the global geological mapping procedure as well as the comparison to Tethys' global spectral surface properties. For this purpose we rescaled the mosaic to a lower map scale of 1 km/pixel, which is sufficient for comparison with the global VIMS map since the latter have generally a lower pixel ground resolution than the ISS images. This is the same approach as used for our geologic mapping of Dione and Rhea (Stephan et al., 2010; Stephan et al., 2012). A map scale of 1 km/pixel is also sufficient to identify global geologic units, individual units within major impact structures. In order to constrain the location of geologic boundaries and in order to characterize a geologic unit as well as to support the investigation of local geological and spectral properties of Tethys, however, we also used the original higher-resolution imaging data to support the mapping procedure. Furthermore, in order to prevent a misinterpretation of VIMS signal due to viewing conditions (Stephan et al., 2012) at the time of the acquisition, simultaneously acquired ISS images were used for comparison.

Although not exclusively designed for the development of digital terrain models (DTMs), individual images provide the opportunity to produce DTMs of regional areas using the stereo-technique like the DTM of Ithaca Chasma already presented in the work of Giese et al. (2007). Previous works (Stephan et al., 2014; Stephan et al., 2012) showed the potential in the possibility to associate spectral properties to local topographic changes like slopes, etc., especially in tectonically formed regions.

2.2. VIMS observations

VIMS consists of two instruments that measure sunlight reflected from the surfaces of the satellites. They generate image cubes in which each pixel represents a spectrum consisting of 352 contiguous spectral channels (Brown et al., 2004). The VIMS V instrument possesses 96 spectral channels that measure radiation between 0.35 and 1.05 μm , while the VIMS IR instrument operates between 0.86 μm to 5.2 μm and collects light in 256 spectral

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