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First far-ultraviolet disk-integrated phase curve analysis of Mimas, Tethys and Dione from the Cassini-UVIS data sets

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ABSTRACT

We perform an analysis of the photometric properties of the icy saturnian satellites at 180 nm, based on the first far-UV disk-integrated phase curves of Mimas, Tethys and Dione. Their interactions with the environment (the E-ring and the magnetosphere) are investigated, leading to a better understanding of the effects of exogenic processes on the system of Saturn. We find that Tethys and Dione have a leading hemisphere brighter than their trailing hemisphere at far-UV wavelengths, while Mimas exhibits a quite uniform reflectance on its surface. No asymmetry is observed between the saturnian and anti-saturnian hemispheres of those satellites, indicating that exogenic processes are important primarily on the leading and trailing hemispheres. Tethys shows a narrower opposition effect, suggesting a more porous regolith on its surface than on Dione and Mimas. This could be the consequence of more significant bombardment by the E-ring grains at the orbit of Tethys. Dione's photometric properties reveal a more absorbing surface, which could be explained by a lower amount of E-ring grain bombardment and/or by the deposit of a darkening agent mainly on its trailing side.

1. Introduction

The midsize satellites of Saturn have been observed since 1980 by two space missions: *Voyager and Cassini*. While the first close-up images were obtained in the early 1980s, the planetary community waited 24 more years for the arrival of the Cassini spacecraft around Saturn on July, 1st 2004, to investigate the saturnian system in detail. For the first time, a significant amount of information on those satellites have been acquired at far-ultraviolet (FUV) wavelengths.

Buratti and Veverka (1984) were the first to analyze Tethys and Dione disk-integrated phase curves, using Voyager clear filter data. No information was available on the opposition surge, due to a lack of data at solar phase angles smaller than 8°. They observed a leading/trailing asymmetry (where the leading hemisphere is centered on 90°W and the trailing hemisphere is centered on 270°W) with a leading hemisphere brighter on Tethys and Dione; they found Mimas to have a slightly brighter trailing hemisphere, despite the poor quality of the data. Verbiscer and Veverka (1992) also reported a slightly brighter trailing hemisphere (TH) on Mimas at 0.48 μm using Voyager data. This leading versus trailing hemisphere brightness has also been predicted by the model of Hamilton and Burns (1994): as written in Note 16 of that paper, the E-ring grains overtaking Mimas in its orbit should primarily impact the trailing side. Buratti et al. (1998) confirmed this result again in 1998, using ground-based data at 0.9 μm.

Moreover, Buratti et al. (1998) showed that at 0.9 μm Mimas, Enceladus, Tethys, Dione and Rhea are far brighter than any other class of object in the Solar System, each of them having a leading hemisphere (LH) geometric albedo greater than 0.70. This is also true in near-UV and visible wavelengths (Buratti and Veverka, 1984; Nelson et al., 1987). The high albedos suggest that these water–ice surfaces contain few low albedo contaminants and also support the idea that the optical properties of the mid-size saturnian satellites are strongly affected by deposits of bright ice grains from the E-ring (Buratti et al., 1998). Previously, no correlations between the geological units and the color and albedo patterns were found for the five midsize satellites of Saturn, suggesting that the photometric properties are due largely to exogenic alterations (Buratti et al., 1990). More recently, in 2007, Verbiscer et al. (2007) used Hubble Space Telescope (HST) data to show a positive correlation between the E-ring grain flux and the geometric albedo of satellites.

Detailed studies of the photometric and spectral properties of the saturnian satellites started with the analysis of the Cassini data sets. Among them, we can note in 2010, the papers of Pitman et al.

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(2010) and Filacchione et al. (2010), which also reported a leading hemisphere brighter than the trailing one on Tethys and Dione, both using the Cassini-VIMS (Visual and Infrared Mapping Spectrometer) instrument. Pitman et al. (2010) analyzed disk-integrated spectrophotometric properties of the five midsize satellites, in the visible and infrared between 0.35 and 5.01 μm, and also derived the bolometric Bond albedos of Mimas (0.67 ± 0.10), Tethys (0.61 ± 0.09) and Dione (0.52 ± 0.08). They gave new refined values of the major photometric quantities for both leading and trailing hemispheres.

An extended study comes from Filacchione et al. (2010), who provided comparative study of the spectral characteristics of the mid-size and minor saturnian satellites. They investigated the visible spectral slopes (0.3–0.55 μm) and found a strong forward scattering component on Tethys. They investigated the disk-integrated composition of the satellites and the amount of contaminant present in the water ice, as well as the grain size distribution. Carbon dioxide was suggested as a possible contaminant of the water ice on the most exterior satellites (Hyperion, Iapetus and Phoebe). That study found no particular hemispheric brightness asymmetry at Mimas; the largest hemispheric albedo dichotomy was found on Dione. A large amount of contaminant covering Dione's trailing side could explain it, as suggested by Clark et al. (2008).

Schenk et al. (2011) created global color maps on the midsize icy satellites in three colors (UV-Green-IR). Color patterns were highlighted, especially on the leading hemispheres of Tethys and Mimas, where a blueish lens shape at the equator, extending ±20° in latitude on Tethys and ±40° on Mimas, was clearly observed. While Voyager images already showed this equatorial band across the leading hemisphere of Tethys (Smith et al., 1981; Stooke, 1989, 2002; Buratti et al., 1990), it was the first time that it was observed on Mimas. Howett et al. (2011, 2012) with Cassini-CIRS near-IR data produced results correlated with the observations of Schenk et al. (2011). A thermal inertia anomaly was discovered, matching the location of the blue lenses on Mimas and Tethys. Energetic electron bombardment is the main hypothesis proposed for both the thermal inertia anomalies and the observed color patterns (Paranicas et al., 2012).

The 1980s and 1990s hosted the development of several photometric models (Hapke, 1981, 1984, 1986; Shkuratov et al., 1999; Lumme and Bowell, 1981; Buratti, 1985). Cassini scientists have thus benefited from this advancement in theory to retrieve more information from phase curves. The greater amount of data of a better quality and resolution brought by Cassini, as well as the better coverage in solar phase angles and these model improvements have led to numerous discoveries about these midsize satellites of Saturn. Cassini provides the first opportunity to observe this region in detail in the FUV domain, over a long period of time and with a wide variety of solar phase angles not accessible from Earth. While acquiring unexpected observations in visible and infrared, the UV represents a third piece of the puzzle to obtain a global understanding of the system of Saturn.

The ultraviolet wavelengths are particularly sensitive to relatively small amounts of surface weathering (Hapke, 2001; Hendrix et al., 2003). By probing the uppermost layers of the icy satellite surfaces, they allow the study of the exogenic processes that alter them, such as bombardment by E-ring grains, charged particles and plasma. Ion bombardment of ices is known to produce defects in the ice. These processes altering the surfaces, create voids and bubbles that affect the light scattering properties of the surface. They can also change the chemistry by trapping gases, which can produce spectral absorption features (Johnson, 1997; Johnson and Quickenden, 1997; Kouchi and Kuroda, 1990; Sack et al., 1992). Heavy (less-penetrating) damaging ions have been seen to brighten surfaces in the visible (Sack et al., 1992). Bombardment of charged particle can implant new chemical species, can drive chemical reactions and species creation, alter grain size and other microstructure and even sputter away the surface.

We present here the first disk-integrated far-UV phase curves of three midsize icy satellites of Saturn: Mimas, Tethys and Dione. The layout of the paper is as follows; Section 2 presents the instrument and datasets. Section 3 deals with the disk-integrated phase curves retrieved from the observations. Section 4 details the Hapke model we use, followed by its results and analysis in Section 5. Section 6 deals with the interpretation of such results.

2. Observations and datasets

2.1. Observations

The UVIS (Ultraviolet Imaging Spectrograph subsystem) instrument, described in detail by Esposito et al. (2004), is composed of two-dimensional CODACON detectors that provide simultaneous spectral and one-dimensional spatial images. The far-UV channel covers wavelengths from 111.5 nm to 191.2 nm. The detector format is 1024 spectral pixels by 64 spatial pixels. Each spectral pixel is 0.25 mrad and each spatial pixel is 1.0 mrad projected on the sky. Our study focuses on observations using the low-resolution slit, giving a spectral resolution of 0.48 nm and a spatial FOV of 1.5 mrad in the spectral dimension.

We use disk-integrated observations spanning the entire Cassini mission from 2004 until the most recent ones in 2013, as listed in Tables A.1, A.2 and A.3 in appendix. A filling factor, which is the ratio of the area of the satellite on the area of a pixel projected to the sky, normalizes each observation to a common distance. As shown in Fig. 1, the satellite usually appears on one or two spatial pixels of the detector. Signals from each pixel containing the satellite are summed. The integration time is usually 120 s, thus an observation of few minutes contains multiple measurements that are averaged.

Background signals, from the Radioisotope Thermoelectric Generators (RTG) and the sky background, are removed prior to

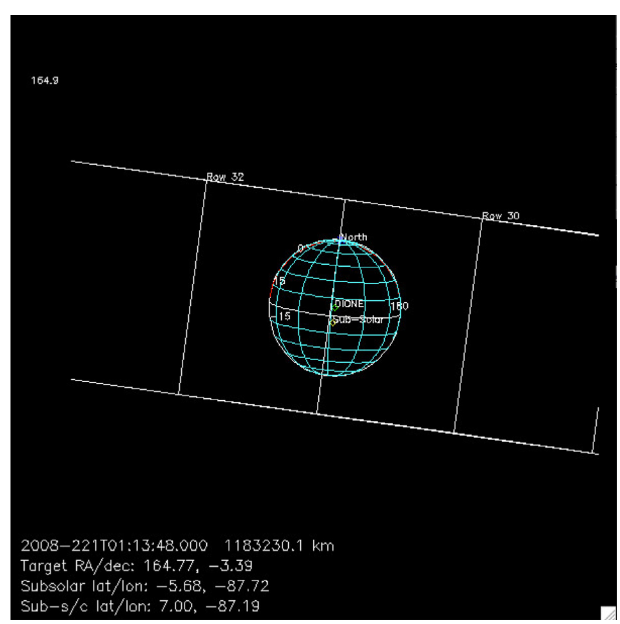

Fig. 1. A sample observation showing the satellite Dione in the UVIS slit. Each rectangle, limited by white lines, represents a spatial pixel. The notations indicate that Dione is partially on pixel 32 and pixel 31. This is a disk-integrated configuration, Dione being smaller than a pixel. On the bottom left, some details are given about the date, time, observational geometry and the position of the spacecraft.