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**DISTRIBUTION OF ICY PARTICLES ACROSS ENCELADUS' SURFACE AS
DERIVED FROM CASSINI-VIMS MEASUREMENTS**

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DISTRIBUTION OF ICY PARTICLES ACROSS ENCELADUS' SURFACE

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Abstract

The surface of Enceladus consists almost completely of water ice. As the band depths of water ice absorptions are sensitive to the size of particles, absorptions can be used to map variations of icy particles across the surface. The Visual and Infrared Mapping Spectrometer (VIMS) observed Enceladus with a high spatial resolution during three Cassini flybys in 2005 (orbits EN 003, EN 004 and EN 011). Based on these data we measured the band depths of water ice absorptions at 1.04 μm , 1.25 μm , 1.5 μm and 2 μm . These band depths were compared to water ice models that represent theoretically calculated reflectance spectra for a range of particle diameters between 2 μm and 1 mm. The agreement between the experimental (VIMS) and model values supports the assumption that pure water ice characterizes the surface of Enceladus and therefore that variations in band depth correspond to variations in water ice particle diameters. Our measurements show that the particle diameter of water ice increases toward younger tectonically altered surface units with the largest particles exposed in relatively “fresh” surface material. The smallest particles were generally found in old densely cratered terrains. The largest particles ($\sim 0.2\text{mm}$) are concentrated in the so called “tiger stripes” at the south pole. In general, the particle diameters are strongly correlated with geologic features and surface ages, indicating a stratigraphic evolution of the surface that is caused by cryovolcanic resurfacing and impact gardening.

Keywords: Enceladus, Saturnian satellites, spectroscopy, water ice, particle size distribution, resurfacing, ice tectonics

Introduction

With its diameter of 504 km, Enceladus is Saturn's sixth largest satellite orbiting at a distance of 238,040 km between Mimas and Tethys within the extended E-Ring. Enceladus is one of the brightest objects in the solar system with a geometric albedo slightly exceeding 1.0 μm at 0.8 μm wavelength (Cruikshank et al., 2005). The high reflectivity is consistent with a surface composed almost of pure water ice as also indicated by its spectral reflectance signature (Cruikshank, 1980; Grundy et al., 1999; Cruikshank et al., 2005; Emery et al., 2005, Brown et al., 2006).

Provinces which show abrupt changes in crater densities and which occur along major tectonic contacts characterize the surface morphology and geology. The major geological provinces are heavily cratered terrain and ridged and fractured plains. Each of these provinces can further be subdivided in terms of specific regional crater densities and complexities as well as their tectonic characteristics (Smith et al., 1982; Squyres et al., 1983; Passey, 1983; Kargel and Pozio, 1996). Prominent geologic features in the heavily cratered plains are relatively shallow medium-sized craters including a few larger ones with bizarre central domes like Ali Baba and Aladdin, differing significantly from central peaks of typical complex craters. Crater diameters range from less than 100 m to a few tens of kilometers (Kargel and Pozio, 1996; Porco et al., 2006). Some craters are elliptical or irregular in shape, indicating tectonic modification of the cratered plains. Rectilinear troughs, scarps and pit chains within the cratered plains also support this. The relief in the cratered plains varies from less than 100 m to about 1000 m (Kargel and Pozio, 1996).

The fractured plains exhibit both negative and positive tectonic relief forms. Troughs, scarps, grooves, and pit chains reflect mainly extensional stress while ridges indicate compressional forces (Passey, 1983). Within the fractured plains, smooth areas, like Sarandib or Diyar Planitiae, are surrounded by sets of lineaments, troughs and ridges. The relief of the scarps,

troughs and ridges varies from less than hundred meters to about 2000 m with the ridges being the highest terrain features (Passey, 1983; Kargel and Pozio, 1996). Troughs are mostly graben, while scarps resemble normal faults. Ridges can be attributed to (1) viscous cryovolcanic effusions, (2) extrusions of warm ice as on Uranus' moons Ariel and Miranda (Jankowski and Squyres, 1988; Croft and Soderblom, 1991; Kargel et al., 1991) (3) folding as a response to crustal stress or (4) volcanic lithospheric loading and downwarping or lithospheric compression along zones of mantle downwelling (Kargel and Pozio, 1996).

Within the fractured terrains, there are flow features resembling glacier-like movements or pasty cryovolcanic deposits (Smith, et al., 1981; Squyres et al., 1983, Kargel and Pozio, 1996; Kargel, 2006, Porco et al., 2006). In particular, the south polar terrain is disrupted by a complex fracture pattern of sinuous scarps, ridges and troughs.

Linear depressions, that have been termed 'tiger stripes' (Porco et al. 2006), are the most prominent features in this area. The tiger stripes are typically ~ 500 m deep, 2 km wide, and reach an extension of ~ 130 km. The depressions are flanked by ridges ~ 100m high. The stripes are spaced about 35 km apart and cross-cutting fractures and ridges with almost no superimposed impact craters characterize the area between the stripes. In late 2005, limb imaging led to the discovery of a plume, over 400 km high, which consisted of forward-scattering particles emanating from the South Polar Region (Porco et al., 2006). These plumes are supplied by distinct jets emanating from the surface in different directions, with the source regions appearing to be identical with the tiger stripes (Porco et al., 2006). Thus, the south polar region has been geologically active in recent times, exposing cryovolcanic active fissures, venting, extrusion and re-deposition of solid particles. The active volcanism confirms present-day resurfacing and helps to understand the high albedo as well as a variety of surface ages found on Enceladus. Crater counts on Enceladus confirm the wide range of surface ages (Kargel and Pozio, 1996; Neukum et al., 2005; Wagner et al., 2005; Porco et al., 2006). Dependent on the flux model used, which can be either lunar-like with steep initial decay

(Neukum, 1985) or constant flux (Zahnle, et al., 2003), the heavily cratered terrain has absolute ages as old as 4.2 billion or 1.7 billion years, respectively. The fractured terrain has been formed either between 3.7 and 1.0 billion years ago in the lunar-like scenario or it is as young as 200 to 10 million years based on the constant flux model. The south polar terrain shows crater ages younger than 100 million to few hundreds of thousands years, respectively, and indicates recent activity in the vicinity of the tiger stripes (Porco et al., 2006).

Enceladus' surface is almost completely dominated by water ice mainly in a crystalline state as shown by near-infrared spectroscopy (Cruikshank, 1980; Grundy et al., 1999; Cruikshank et al., 2005; Emery et al., 2005, Brown et al., 2006). Other constituents are only of minor importance and are restricted to certain areas. Some telescopic spectra show weak features associated with NH_3 absorptions (Grundy et al., 1999; Emery et al., 2005) whereas other spectra do not (Cruikshank et al., 2005). No features compatible with NH_3 absorptions have been detected in VIMS spectra, indicating an upper limit to NH_3 content on the surface of no more than 2% (Brown et al., 2006). The lack of NH_3 might be due to its higher volatility and to the higher temperatures near the eruption centers, which may have caused its depletion over the last 4 billion years or, alternatively, hydrothermal circulation may have sequestered it into interior rocks (Kargel, 2006). Another constituent found in VIMS spectra is free CO_2 -ice in small amounts on a global scale and in higher concentrations near the South Polar Region (Brown et al., 2006). Within the very young tiger stripes, CO_2 is highly abundant but in a more complex mixture with water ice due to the higher temperatures in this area (Saur and Strobel, 2005), which cause free CO_2 -ice to rapidly migrate northward to colder temperatures (Brown et al., 2006). However, the high concentration of complex CO_2 in the tiger stripes requires active replenishment by cryovolcanic activity in this area (Brown et al., 2006). VIMS spectra also indicate significant concentrations of simple organics in the tiger stripes (Brown et al., 2006).

Although the surface of Enceladus is mainly composed of pure water ice the VIMS spectra show significant variations across the surface mainly in the H₂O-ice absorption bands.

Band depth is sensitive to the amount of ice, contamination by other materials as well as to the particle sizes of the H₂O-ice crystals (Clark, 1981a, 1981b, 1983; Clark and Lucey, 1984; Lucey and Clark, 1984). Due to the high concentration of water ice the spectral variation on Enceladus' surface might directly be correlated with varying particle diameters. Thus, spatial mapping of these spectral variations may yield the distribution of particle sizes across the surface. Furthermore, if particle sizes correlate with geological surface units, additional information about processes of ice deposition and ice weathering can be derived.

Visible and Infrared Mapping Spectrometer (VIMS) observations of Enceladus

VIMS is a mapping spectrometer generating 'image cubes' consistent of 352 simultaneously exposed two-dimensional images in 352 spectral channels (Brown et al., 2004). These spectral channels cover a wavelength range from 0.35 μm to 5.2 μm , producing significant spectral signatures of water ice on Enceladus including absorptions at 1.04 μm , 1.25 μm , 1.5 μm , 1.65 μm , 2.0 μm and several spectral absorption features in the 3 μm range. After spectral and radiometric calibration (Brown et al., 2004; McCord et al., 2004; Coradini et al., 2004) the spectral resolution of 8 nm and 16 nm for the visible and infrared, respectively, allows studying these absorptions in detail. The maximum spatial format reaches 64 by 64 pixels with a nominal pixel size of 0.5 x 0.5 mrad (Brown et al., 2004). By geometric rectification of each VIMS pixel and by combining single VIMS observations into mosaics, the spectral reflectance characteristics of a surface can be compared on a pixel-by-pixel basis (Jaumann et al., 2006).

VIMS observations of Enceladus were performed during the Cassini flybys EN 003, EN 004 and EN 011, which took place in February, March and July 2005. Forty-seven VIMS cubes

were acquired during these orbits with resolutions ranging from 30 km/pix to 5 km/pixel (Tab.1). All observations include the region between 150° and 280°W, the anti-Saturnian part of the trailing hemisphere. While orbits EN 003 and EN 004 mostly cover the northern hemisphere and the equatorial region of Enceladus, VIMS data acquired during orbit EN 011 reached regions farther south including the south pole.

[Table 1]

All VIMS cubes are radiometrically calibrated, i.e. the raw data number (DN) signal of each VIMS pixel is converted into physical values of reflectance (I/F). The specific energy (I_λ) is converted using the instrument's spectro-radiometric response function $R(\lambda)$ in photons per DN (Brown et al., 2004).

$$I_\lambda = \text{DN} \tau^{-1} R(\lambda) h c \lambda^{-1} (A \Omega \delta \lambda)^{-1}, \quad (\text{eq. 1})$$

where τ is the exposure time in seconds, h is Planck's constant, c the speed of light, λ is the wavelength the particular VIMS bandpass, $\delta \lambda$ is the size of the corresponding wavelength bin, A is the area of the VIMS mirror, and Ω is the solid angle subtended by a pixel in steradians.

The reflectance is finally arrived at by dividing I_λ by a solar spectrum (Thekekara, 1973) with the solar flux at the instantaneous Sun-target distance, $R_{\odot}$:

$$I / F = I_\lambda / F_{I,\lambda} (R_{\odot} / R_{\oplus})^2, \quad (\text{eq. 2})$$

where $F_{I,\lambda}$ is the specific solar flux at 1 astronomical units $R_{\oplus}$.

In addition, each VIMS pixel is geometrically rectified and converted into a map projected image cube in order to determine the geographic position of each pixel on Enceladus' surface. The spectral properties can be attributed to the geographic position and thus be correlated with geological and geomorphological surface features. The projected cubes are combined into VIMS mosaics in order to produce spectral variation maps. In order to avoid changes of

the original spectral signal, this re-projection is performed using the nearest neighbor algorithm, which merely shifts a single VIMS pixel into the new location but does not interpolate between several VIMS pixels. The rectification and mosaicking process of VIMS cubes is described in detail in Jaumann et al. (2006).

The band depth of a specific absorption is defined by the reflectance value at the absorption center relative to the reflectance value of the corresponding continuum (Clark and Roush, 1984):

$$D = 1 - R_b/R_c, \quad (\text{eq. 3})$$

where D is the band depth, R_b is the reflectance at the absorption band center, and R_c is the reflectance of the continuum at the band center with $b, c \in \{1.04 \mu\text{m}, 1.25 \mu\text{m}, 1.5 \mu\text{m}, 2.0 \mu\text{m}\}$. The advantage of this relative approach to estimating band depths is that effects due to varying illumination conditions (e.g. viewing geometry, macroscopic and microscopic roughness, shadowing) (Hapke, 1981, 1984, 1986, 1993; Skuratow et al., 1999; Douté and Schmitt, 1998), are minimized because both the reflectance at the specific wavelength position and the corresponding continuum are affected by these parameters similarly. Thus, absorption band depths become comparable even when the corresponding reflectance spectra have been observed under different illumination conditions (Clark and Roush, 1984; Stephan, 2006). Furthermore, comparable observations on Earth show no topographic effects in continuum-removed band depth maps (Clark et al., 2003). Also, continuum-removed band depth maps derived from NIMS and VIMS observations of the Jovian satellite Ganymed and the Saturnian satellites Dione and indicate that continuum-removed band depth maps show essentially no topographic effects, except at extreme viewing geometries, such as encountered at the limb, where both incident and emission angles approach 90° (Hibbitts et al., 2003; Clark et al., 2005; Clark et al. 2007). This error induced by photometric effects particularly at high phase angles can amount to about 50%, which, however, is still well below the measured band depth variances of 4 and greater.

Spectral characteristics of water ice with different particle diameters

The spectral characteristic of water ice in the near-infrared wavelength region is well defined by distinct absorptions (Fig. 1). These absorptions vary in depth, mainly as a function of the wavelength variation of the refractive index of ice, of the particle diameter distribution of ice and of the amount of impurities in the surface material whose refractive indices are substantially different from those of water ice (Clark, 1981a, 1981b, 1983; Clark and Lucey, 1984; Lucey and Clark, 1984; Dozier, 1989).

The probability for a photon to be absorbed by an ice particle is higher if the ice particle is large, e.g. the distance through which light will travel within the ice particle is long. This effect causes the deepening of water ice absorptions and an increase in the reflectance slope between 1 μm and 3 μm with increasing particle diameter. Usually surface ice on satellite surfaces is contaminated by impurities, and absorption band depth variations depend also on this effect (e.g. Sill and Clark, 1982). However, the surface of Enceladus is mostly covered by pure crystalline water ice everywhere (Brown et al., 2006; Newman et al., 2006) and thus variations of the band depths are mainly due to variations in particle size. Another factor that might increase the absorptions of water ice across an extended surface is that of changing photometric observing conditions. However, phase function effects on reflectance (e.g. Hapke, 1981, 1984, 1986, 1993;) can be minimized by estimating the absorption depth relative to the continuum (Clark and Roush, 1984). The bidirectional reflectance distribution function is also affected by shadowing due to topographic effects at a macro scale (tens of centimetres to instrument pixel size) and at a micro scale (comparable to particle size), which might alter band depth. For Enceladus we do not have any quantitative information describing these parameters. However, photometric models (e.g. Hapke, 1981, 1984, 1986, 1993;) describe these parameters on sub-pixels scales also as multiplicative terms and the relative

estimation of band depths reduces this effect. While the relative approach cannot completely correct for all unknown sub-pixel photometric surface properties and while the remaining effects may increase the noise, these effects are minor compared to variations in composition or particle size.

Based on these considerations, the relative band depth measurements are primarily sensitive to particle size and can, thus, be used to map particle diameter variations across the surface of Enceladus.

Figure 2 shows the spectral signature of a theoretical water ice spectra of particles with different diameters as derived from a model of Hansen and McCord (2004). This model relies on optical constants from Bergren et al., (1978), Clapp et al., (1995), Grundy and Schmitt, (1998) for cold ice at temperatures below 110°K. A band depth to grain size model as developed by Clark and Lucey, (1984) relies on optical constants by Warren, (1984) derived for warmer ice yield particle sizes that are increased by about 30% with respect to the Hansen and McCord (2004) model. The discrepancy between both models may be due to differences in ice temperatures. However, both models show the same relative correlations and trends of band depth and particle size and fit the Enceladus spectra within the overall scattering of our band depth measurements that amount to 30%. As temperatures also vary on Enceladus, particles in warmer regions such as the south pole may more likely fit the upper end of the error bar.

[Figure 1]

[Figure 2]

The model spectra were used to correlate the depth of the water ice absorption bands at 1.04 μm , 1.25 μm , 1.5 μm , and 2.0 μm with particle diameters between 2 μm and 0.2 mm. Each of

the absorption depths develop differently with increasing particle diameter and reveals characteristic band depth to size correlation curves (Stephan, 2006) that are characterized by

$$y = a_i x^{0.5}, \quad (\text{eq. 4})$$

with y describing band depth and x particle size and a is a scaling parameter for each absorption band $i \in \{1.04 \mu\text{m}, 1.25 \mu\text{m}, 1.5 \mu\text{m}, 2.0 \mu\text{m}\}$ (Fig. 3).

[Figure 3]

The correlation of band depths with particle diameters allows identifying the size of particles in the surface material of Enceladus and mapping their distribution across the surface.

Water ice particles on Enceladus

The spatial resolution of VIMS image cubes (Tab. 1) is sufficient to distinguish the three major geologic units on Enceladus: heavily cratered terrain (hct), fractured and ridged terrain (frt) and complex tectonically deformed regions (tdr) of troughs and ridges known as Sulci, which include the tiger stripes in the south pole region. Although it is assumed that these geological units are composed completely of water ice, the band depths of the water ice absorptions change significantly between the individual units with each unit owing its own characteristic range of water ice absorption band depths.

Characteristic spectra for these three geological units are adjusted to the model spectra of different particle sizes as shown in figure 4. Although the VIMS spectra contain some noise and are somewhat marred by photometric effects, which explains most of the observed deviations from the model spectra, the main water ice absorptions at $1.04 \mu\text{m}$, $1.25 \mu\text{m}$, $1.5 \mu\text{m}$, and $2.0 \mu\text{m}$ fit well into the particle size scheme of the model spectra with heavily cratered terrain (hct) having the shallowest absorptions, absorptions in fractured and ridged

terrain (frt) being deeper and the absorptions in tectonically deformed regions (tdr) being the deepest.

[Figure 4]

However, in order to make measurements of different parts of the surface comparable and avoid photometric effects, relative band depth to band depth correlations of the absorptions at 1.04 and 1.25 μm and at 1.5 and 2 μm are also considered. Fig. 5 shows absorptions (band depth) at different wavelengths plotted against each other for each pixel of the EN 011 observation that covers the south pole and parts of the anti-Saturnian hemisphere up to 30° N.

[Figure 5]

A comparison of the band depth at 1.04 μm with that at 1.25 μm suggest a simple linear correlation:

$$y_{1.04} = 0.44 y_{1.25}, \quad (\text{eq. 5})$$

where y_i are band depths at wavelength $i \in \{1.04 \mu\text{m}, 1.25 \mu\text{m}\}$. Comparing the resulting band depths to particle size values shows that all absorption measurements in these wavelengths are linearly correlated with particle sizes. In addition, the weak bands tend to be sensitive to the large size component due to the greater path length in ice that acts as an efficient photon trap. The heavily cratered terrain is composed of particles with a main diameter of 10 μm or less. Particles of the fractured and ridged terrain fall mainly in the range between 10 μm and about 50 μm , and the tectonically deformed regions exhibit main particle diameters of > 50 μm up to diameters of more than 150 μm within the south polar tiger stripes. The scattering of the data is mostly due to uncertainties induced by instrument noise ($S/N = 30$ at 1 μm) that affects

these weak absorptions and results in an accuracy of the particle size estimation of a mere 30%.

Although the band depth to band depth plot between the absorptions at 1.5 μm and at 2.0 μm shows less scattering due to a higher signal to noise ratio ($S/N = 130$ at 1.5 μm) and thus deeper bands, the comparison with the band depth to particle size model indicates a non-linear behavior of this correlation. In addition, the deeper bands are more sensitive to the small size component since these particles control the fraction of photons that can be reflected off the medium without being absorbed due to the multiple ice/void interface of small grains.

The correlation can best be described by a non-linear approximation:

$$y_{1.5} = a (y_{2.0})^2 + b y_{2.0} \quad (\text{eq. 6})$$

where y_i describes the band depths at wavelength $i \in \{1.5 \mu\text{m}, 2.0 \mu\text{m}\}$, a is the portion of particles smaller than a threshold particle diameter of $\varnothing_j$ and $b = (1 - a)$ is the portion of particles with diameter $\varnothing_j$ within a pixel.

Our results show that the band depths at different wavelength are correlated in the same way as the theoretical spectra (Fig. 5). These observed correlations are described using eqs. 5 and 6. Due to the scattering of the short wavelength data a linear approximation is the best fit to these data (Fig 5 left). For the longer-wavelength data that have a better accuracy a non-linear function (eq. 6) is the best approximation to describe these measurements. Our interpretation of the non-linearity is that there might be a mixing of different particles within one pixel that can roughly be estimated by assuming that the parameter a and b of eq. 6 are controlled by the portions of different particle diameters.

According to the 1.04 μm to 1.25 μm band depth correlation, the heavily cratered terrains (hct) exhibit a mean particle size of $15 \pm 5 \mu\text{m}$ within a VIMS pixel. The particle size mixing as derived from the 1.5 μm to 2.0 μm band depth correlation indicates a distribution of 25% particles with diameters of about 15 μm and larger, and 75% $< 15 \mu\text{m}$ within this pixel. Icy particles in the fractured and ridged terrain (frt) peak at a size of about $30 \pm 10 \mu\text{m}$ with an

intimate mixing characteristic of $70\% < 30 \mu\text{m}$. The tectonically deformed regions (tdr) exhibit particles ranging from $40 \mu\text{m}$ to about $120 \mu\text{m}$ with the largest ones located close to the center of the south polar tiger stripes. According to eq. 6, one pixel within this unit might contain about 90% particles smaller than $80 \pm 20 \mu\text{m}$ and about 2 % larger than $100 \mu\text{m}$.

The heavily cratered terrain and adjacent fractured and ridged plains are best represented by an area that was observed by VIMS during orbit EN 004 and is located close to the equator of Enceladus between 210 and 160°W (Fig. 6). The spatial resolution of the VIMS cubes is about 5 km/pixel

[Figure 6]

This eastern heavily cratered region (Fig. 6) exhibits the lowest band depth corresponding to particle diameters $\leq 20 \mu\text{m}$. Local increases of particle diameters up to $30 \pm 10 \mu\text{m}$ seems to be correlated either with impact craters that expose fresh material from underneath or have locally melted the water crust, or with ridges and fractures marking the transition zone to the uncratered plains. The latter extend in westward direction from the heavily cratered terrain with longitudes larger than 210°W . The ridged and fractured plains to the west exhibit slightly deeper absorptions that indicate particle diameters of about $30 \pm 10 \mu\text{m}$ with the largest particles reaching sizes up to $60 \pm 20 \mu\text{m}$ directly at tectonic fractures, ridges and grabens.

The tectonically deformed regions are best represented by the tiger stripes at the south pole. Figure 7 shows the VIMS mosaic based on observation data acquired during orbit EN 011 (Tab. 1) that in particular include the south pole area with its best spatial resolution at about 5 km/pixel

[Figure 7]

The tectonically deformed region of the tiger stripes are surrounded by fractured and ridged plains that show particle diameters $< 40 \mu\text{m}$. The tiger stripes themselves can be divided into a larger outer and a smaller inner zone. The outer zone has particle diameters in the range of $60 \pm 20 \mu\text{m}$ to $100 \pm 30 \mu\text{m}$. Particles of the inner zone are definitely larger than $100 \mu\text{m}$ and even reach sizes $> 150 \mu\text{m}$.

The southern hemisphere exhibits particle diameters ranging from the small sizes found in the cratered terrain to the largest icy particles on the satellite (Fig. 8).

The area surrounding the pole has the largest particle diameters peaking in the center of the tiger stripes. Particle diameters decrease outward in both directions. The wider area around the pole has significantly smaller particles. Between 150° and 210° W and north of 45° S as well as 330° to 30° W and north of 60° S the pole is surrounded by heavily cratered terrain, which explains the small particle diameters. The area between 240° to 300° W and 30° to 60° S also exhibits particle diameters $< 30 \mu\text{m}$. Although this terrain has ridges and is fractured it contains significantly more impacts than the fractured and ridged plains. This area also has a well-defined geological boundary with the younger ridged and fractured plains that cut and overlay most of the older area (c.f. Porco et al., 2006, Fig. 2A). These area of smaller particles sizes is cut by two north-trending tectonically deformed zones at about 255° W and 300° W (Fig. 8). A third tectonically deformed zone trends northward between 190° W and 230° W, separating the more densely cratered fractured and ridged plains to the southwest of the western heavily cratered terrain (Fig. 8). All three tectonically deformed zones exhibit particle sizes comparable to those of the fracture and ridged plains, with the largest sizes of about $60 \pm 20 \mu\text{m}$ to be found directly at tectonic fractures, ridges and grabens. These tectonically deformed north-trending zones at 255° W and between 190° and 230° W are extensions of the

tiger stripes and show a similar distribution of particle diameters with the highest values in the center of the fractures.

[Figure 8]

Particle diameter distribution

The distribution of particle diameters is calculated based on the absorption band depth at $1.5\ \mu\text{m}$ as a function of pixel frequency. Although the pixel sizes are relatively large and the approach assumes a mean particle diameter for each pixel this can be used as a first-order estimate of the distribution of icy particles on Enceladus. VIMS so far covers 30% of Enceladus' surface. The particle size distribution is dominated by particles of $15 \pm 5\ \mu\text{m}$ to $60 \pm 20\ \mu\text{m}$ with a peak at about $20\ \mu\text{m}$ (Fig. 9a). Most of the investigated area ($\sim 90\%$) is heavily cratered terrain and, fractured and ridged plains that are dominated by particles $< 30\ \mu\text{m}$. The remaining area of particle diameters ranging from $30 \pm 10\ \mu\text{m}$ to $100 \pm 30\ \mu\text{m}$ relates to tectonically deformed regions like the tiger stripes at the south pole and has a different size to pixel frequency distribution pattern (Fig. 9b). Within the tiger stripe area the size distribution is shifted by a factor of 2 to larger particles with respect to the overall distribution, which shows a significantly higher contribution of particles $> 40\ \mu\text{m}$. This is consistent with the intimate mixing model that shows a size distribution ranging between $15 \pm 5\ \mu\text{m}$ to $100 \pm 30\ \mu\text{m}$ with a peak at about $20\ \mu\text{m}$ and a remaining portion of about 10% with particles $> 80\ \mu\text{m}$ (Fig. 9c).

[Figure 9]

An additional characteristic of the tectonically deformed regions is the symmetric distribution of particle diameters (Fig. 10). The largest particles are concentrated in the center of the tectonically deformed regions that are characterized by a deep fracture, or set of fractures, bordered by ridges that separate them from adjacent ridged plains. Particle diameters decrease away from the fracture to both sides continuously, indicating a correlation between particle diameters and geological surface forming processes.

[Figure 10]

Discussion

The distribution of icy particles unambiguously fits with the morphological as well as geological terrain types. Although there are continuous transitions between terrains, the heavily cratered terrain, fractured and ridged terrain and tectonically deformed regions, each one falls into a distinct particle diameter class. This suggests a correlation between surface-forming processes and the development of the microstructure of the ice. The smallest particles are concentrated in the heavily cratered terrain, which represents the oldest surfaces on Enceladus. The largest particles are concentrated in the inner zones of the tectonically deformed regions, which are the youngest geologic features of Enceladus.

Surface ages as derived from the impact flux models of Neukum, (1985), Neukum et al., (2005), and Zahnle et al., (2003), correlate with the particle diameters of the corresponding geological units. According to the lunar-like impact flux model of Neukum, (1985), and Neukum et al. (2005), the heavily cratered terrain is about 4.1 billion years old, whereas the fractured and ridged plains were formed between 3.7 and 1 billion years ago. The tectonically deformed regions are younger than 1 billion years and reach ages at the south pole that range from younger than 100 million to only a few million years and can even be as young as recent

surface units in the tiger stripes (Porco, et al., 2006). Based on the constant impact flux model of Zahnle et al., (2003), the ages are significantly younger but still follow the same stratigraphic sequence, i.e., heavily cratered terrain is older than 1.7 billion years, fractured and ridged plains are as young as 170 to 10 million years and the tectonically deformed regions are not older than 1 million years. In the constant flux model based on the preferential impact of cometary bodies, Zahnle et al. (2001) discussed that cratering asymmetries might occur between the apex (longitude 90° W) and antapex points (longitude 270° W) of synchronously orbiting satellites, with surfaces near the apex point being much more densely cratered than near the antapex point for the same surface age. While the authors initially inferred from Voyager imagery that such an asymmetry is likely to have occurred on Enceladus, new Cassini ISS image data have shown that this is not the case. Instead, the surface in the apex hemisphere is practically devoid of craters, as a global mosaic of Enceladus demonstrates (c.f. image PIA08342: <http://photojournal.jpl.nasa.gov>). This clearly suggests that crater frequencies reflect relative surface ages between geologic units, and that the ages of these different geologic terrains also directly correlate with the size of icy particles (Fig. 11). As a consequence, micrometeorite impacts with different impact rates between the apex and antapex points can also be ruled out as causes for differences in particle sizes.

[Figure 11]

The active plume above the south pole (Porco et al., 2006), the recent ages and large particle diameters of the inner fractures in the tiger stripes suggest that cryovolcanic eruptions may have deposited icy material on the surface. As large icy particles are heavy, they tend to be concentrated closer to the vent. Another indication for the formation of large particles close to the vent is temperature. Higher temperatures support the growth of large particles (Clark et al., 1983) and indeed CIRS measurements across the tiger stripes indicate the highest

temperatures (Spencer et al., 2006) exactly in those areas where VIMS identifies the largest ice particles (Fig. 12).

[Figure 12]

In the closest vicinity of eruption centers, particle diameters should reflect the distribution of ejection energy, which can be seen in the profiles of figure 10. However, particle diameter distribution is not only a function of eruption dynamics but also depends on surface weathering processes. Sputtering and especially high velocity E-ring particle impacts cause comminution of icy material. Impact gardening also supports the disruption of surface particles. The mechanical decay of particles is thus dependent on the time for which a surface element is exposed to micrometeorite bombardment. Due to this weathering process the regolith of the oldest areas should exhibit the smallest particles. In addition, the absence of a small particulate regolith in the tectonically deformed regions, especially the tiger stripes, also indicates that the material was either emplaced recently and/or has been undergoing thermal alteration.

According to the Neukum (1985) and Neukum et al. (2005) age models, particle sizes have continuously decreased over the last 4 billion years (Fig. 11). It took about a billion years to reduce the particle diameter by a factor of 2 (Fig. 11). For heavily cratered terrains, the particle decay rate as derived from the Neukum (1985) age model is comparable with that of the Zahnle et al. (2003) age model. However, the latter assumes a much faster decay rate in the tectonically deformed regions and in the ridged and fractured terrain, according to which it has taken only about 100 million years to reduce the particle diameters by a factor of 2. The reduction of particle diameters with time as derived from the Neukum (1985) model indicates a possible equilibrium between the formation of icy particles and their disruption by space weathering, suggesting geologic activities over a time span of about 4 billion years, at least

localized and episodically. The reduction in particle diameter with time as derived from the Zahnle et al. (2003) age model suggests a very short period of less than 200 million years for rapid comminuting of particles. According to this model, particle sizes would be reduced by about a factor of 10 within a billion years. This is inconsistent with the lower decay rate for older particles (heavily cratered terrain) in the same model. A possible explanation is that the particle diameters are primarily dominated by the lateral deposition of new material rather than by space weathering, not only in the tectonically deformed regions but also in the ridged and fractures terrains.

From the distribution of particle sizes across the surface of Enceladus we can conclude that the largest particle diameters are inside the tectonically deformed regions, with a decrease in size outwards from the fractures. This is valid not only for the recent tiger stripes but also for older tectonically deformed regions (Fig. 10). In general particle diameters decrease outward from the tectonic fractures. This correlation is mapped within a mosaic of the 1.5 μm absorption band depth of orbits EN 004 and EN011 covering the anti-Saturnian part of the trailing hemisphere from pole to pole (Fig. 13).

[Figure 13]

The basic correlation between particle diameter, geologic unit and age can be observed independently of the age model used. This suggests the following relative sequence of stratigraphic events: (1) Formation of a primary crust (heavily cratered terrain). (2) Mechanical weathering of the surface particles by micro-impacts and sputtering during the last 4 billion years. (2) Tectonic disruption of the surface and deposition of new material with large particles. This process was probably repeated multiple times and formed the widespread ridged and fractured terrains. Although this newly deposited material has undergone mechanical weathering of the particles by micro-impacts and sputtering, these particles are

larger due to their shorter exposure time. (4) Recent deposition of larger particles in the south polar region. Fig. 13 shows a broad band of relatively strong 1.5 μm absorptions, and large particles trending from the south pole towards north exactly coincide with the areas of the mapped fractures (Kargel and Pozio, 1996; Porco et al., 2006). The relationship of the northward-trending fracture zone with that of the tiger stripes and the associated particle size distribution in both areas (Fig. 13) suggests a probable genetic correlation. If the larger particles in the tectonically deformed regions are of the same cryovolcanic origin, the volcanic activity must have changed with time. The south polar region as the youngest and partly still active zone and the older northward-trending tectonic region with its older but still relatively large particles may suggest a change in the eruption history. However, there are still different possibilities to explain this observation: (1) The eruption zones and thus the internal heat distribution may have moved from north to south within the last billion years with respect to the Neukum (1985) and Neukum et al. (2005) time scale, or within the last 200 million years according to the Zahnle et al. (2003) time scale, with the recent south polar tiger stripes marking the actual center of the volcanic activity on Enceladus. (2) Cryovolcanic eruptions could have occurred all over the satellite, dependent on the age model, for the last billion or million years, respectively, and shrunk to a small zone at the south pole, which would be indicative of a probable decrease in internal heat transfer. (3) The intensity of cryovolcanic eruptions was different at different locations and times with a maximum in the south polar region.

So far we have only $\sim 30\%$ high-resolution VIMS coverage of the surface. It is therefore difficult to distinguish between the models. However, tectonically deformed areas are also exposed in regions not yet covered by Cassini (Kargel and Pozio, 1996). If these geologic features show the same particle diameter characteristics it might be possible to decipher the global volcanic history of Enceladus once the data are available.

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Tables

Tab. 1: Parameters of VIMS observations acquired during Cassini orbits EN 003, EN 004 and EN 011.

Figure captions

Fig. 1: Spectral signatures of crystalline water ice with absorption bands at 1.04 μm , 1.25 μm , 1.5 μm , 1.65 μm , 2.0 μm , and several absorption features in the 3 μm range.

Fig. 2: Spectral signatures of water ice with different particle diameters (Hansen and McCord 2004).

Fig. 3: Absorption band depth measured relative to the continuum as a function of particle size, each one corresponding to a mono-sized granular medium.

Fig. 4: Average VIMS spectra showing the heavily cratered terrain (hct) (top), the fractured and ridged plains (frp) (middle) and the tectonically deformed region (tdr) (bottom) as measured in orbit EN 011 compared to theoretical water ice spectra at different particle diameters. All spectra are referred to the continuum (see text). The main absorption at 1.04 μm , 1.25 μm , 1.5 μm , 2.0 μm , fit well with the model indicating the pure ice characteristics of the surface. The gap in the VIMS spectra at 1.7 μm is due to a filter gap of the instrument.

Fig. 5: Band depth to band depth plot for 1.04 μm to 1.25 μm and 1.5 μm to 2.0 μm for absorptions measured globally (orbit EN 011) with resolutions < 30 km/pixel. Absorptions at 1.04 and 1.25 μm indicate a linear correlation with particle size ($y_{1.04} = 0.44 y_{1.25}$). Absorptions at 1.5 and 2 μm are best described by an intimate mixing model ($y_{1.5} = a (y_{2.0})^2 + b y_{2.0}$) (see also discussion in the text).

Fig 6: Type location of heavily cratered terrain and fractured and ridged plains in VIMS cubes at ground pixel resolutions of about 5 km/pixel acquired during orbit EN 004. Upper left: position on Enceladus; upper right: geologic map; lower left: albedo at 1.5 μm ; lower right: absorption band depth at 1.5 μm indicating increasing particle diameters from blue to red.

Fig. 7: Type location of tectonically deformed (tiger stripes) areas in VIMS image cubes at ground pixel resolutions of about 5 km/pixel acquired during orbit EN 004. Upper left: position on Enceladus; upper right: geologic map; lower left: albedo at 1.5 μm ; lower right: absorption band depth at 1.5 μm indicating increasing particle diameters from blue to red. Line b indicate the profile in Fig. 10.

Fig. 8: VIMS cube image of the southern hemisphere (orbit EN 011) with ground pixel resolutions < 30 km/pixel. Left: albedo at 1.5 μm ; middle: geologic map; right: absorption band depth at 1.5 μm indicating increasing particle diameters from blue to red. Lines a and b indicate the profiles in Fig. 10.

Fig. 9: Particle size distribution: a) size to pixel frequency distribution on the anti-Saturnian part of the trailing side ($180^\circ - 270^\circ\text{W}$); b) size to pixel frequency distribution of the south

pole area ($70^\circ - 90^\circ$ S); c) size distribution as derived from the intimate mixing model ($y_{1,5} = a (y_{2,0})^2 + b y_{2,0}$) used to fit the observed data.

Fig. 10: Distribution of particle diameters across the fractures of the tiger stripes and a fracture in the northern fractured and ridged plains at $30^\circ\text{N} / 220^\circ\text{W}$. For the location of the profiles see figures 7 and 8. The subset indicates the stripe in Fig. 12

Fig. 11: Correlation of particle diameters and surface ages of the three terrain types: heavily cratered terrain (hct), fractured and ridged plains (frp) and tectonically deformed regions (tdr). The ages are from Neukum (1985), Neukum et al. (2005), and Zahnle et al. (2003) impact flux models, respectively.

Fig. 12: Comparison of the temperature profile in the tiger stripe region as determined by the Cassini-CIRS instrument (Spencer et al., 2006) to the particle diameter estimation by VIMS at $1.5 \mu\text{m}$ (see also Fig. 10). Largest particles occur at the highest temperatures.

Fig. 13 – Mosaic of orbits EN 004 and EN 011 show the anti-Saturnian part of the trailing hemisphere: left: albedo at $1.5 \mu\text{m}$; middle: geologic map; right: absorption band depth at $1.5 \mu\text{m}$ indicating increasing particle diameters from blue to red.

Tables

Orbit #	Date	Distance at closest approach	Phase angle at closest approach	# of cubes	Resolution (km/pixel)	Geographic position
EN 003	17/02/2005	1175.7 km	114°	17	25.94 – 5.85	57°N – 73°S / 245°-18°W
EN 004	09/03/2005	499.9 km	43.1°	7	10.28 – 4.24	65°N – 29°S / 155 – 265°W
EN 011	14/07/2005	169.4 km	63.4°	23	30.1 – 5.25	32°N – 90°S / 151 – 267°W

Tab.1