Publication Year	2017
Acceptance in OA@INAF	2020-09-10T13:50:34Z
Title	Deciphering sub-micron ice particles on Enceladus surface
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DOI	10.1016/j.icarus.2017.02.012
Handle	http://hdl.handle.net/20.500.12386/27289
Journal	ICARUS
Number	290

Deciphering sub-micron ice particles on Enceladus surface

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1 Abstract

The surface of Saturn's moon Enceladus is composed primarily by pure water ice. The Cassini spacecraft has observed present-day geologic activity at the moon's South Polar Region, related with the formation and feeding of Saturn's E-ring. Plumes of micron-sized particles, composed of water ice and other non-ice contaminants (e.g., CO_2, NH_3, CH_4), erupt from four terrain's fractures named Tiger Stripes. Some of this material falls back on Enceladus' surface to form deposits that extend to the North at ~40°W and ~220°W, with the highest concentration found at the South Pole. In this work we analyzed VIMS-IR data to identify plumes deposits across Enceladus' surface through the variation in band depth of the main water ice spectral features. To characterize the global variation of water ice band depths across Enceladus, the entire surface was sampled with an angular resolution of 1° in both latitude and longitude, and for each angular bin we averaged the value of all spectral indices as retrieved by VIMS. The position of the plumes' deposits predicted by theoretical models display a good match with water ice band depths' maps on the trailing hemisphere, whereas they diverge significantly on the leading side. Space weathering processes acting on Enceladus' surface ionize and break up water ice molecules, resulting in the formation of particles smaller than one micron. We also mapped the spectral indices for sub-micron particles and we compared the results with the plumes deposits models. Again, a satisfactory match is observed on the trailing hemisphere only. Finally, we investigated the variation of the depth of the water ice absorption bands as a function of the phase angle. In the visible range, some terrains surrounding the Tiger Stripes show a decrease in albedo when the phase angle is smaller than 10°. This unusual effect cannot be confirmed by near infrared data, since observations with a phase angle lower than 10° are not available. For phase angle values greater than 10°, the depth of the water ice features remains quite constant within a broad range of phase angle values.

2 Introduction

Enceladus is a small (mean radius 252 km), icy, and geologically active moon of Saturn. Ever since its discovery by William Herschel in 1789, Enceladus has been the subject of a large number of investigations, even though its small size made ground-based observations challenging (Smith et al., 1981).

The Voyager 1 spacecraft provided the very first remote sensing observation of

Enceladus, back in November 1980. However, the coverage was limited and the spatial resolution of those images was coarse. The surface of Enceladus was shown to be smoother, and with a higher albedo than those of the other Saturnian satellites imaged under comparable observation conditions, leading Smith et al. (1981) to conclude that craters on Enceladus may be more subdued than those found on other icy satellites.

Still in the Voyager era, Terrile and Tokunaga (1980) started a ground-based campaign devoted to Saturn's E-ring, during which they noticed a pronounced peak in brightness, correlated with the orbital position of Enceladus. From these observations Terrile and Cook (1981) argued about a possible outgassing activity on Enceladus, possibly supported by a liquid layer existing under a thick crust as formulated by Cassen et al. (1979) and by the estimated amount of heat generated by tidal forces induced by the 2:1 resonance with Saturn's midsize satellite Dione (Yoder, 1979).

In August 1981, Voyager 2 acquired images with spatial resolution up to 25 km/px, which is sufficient to undertake a tectonic and geologic analysis, leading to the identification of five terrain units (Smith et al., 1982). The large diversities in terrain types and crater relaxation opened questions about the thermal history of Enceladus, and clues on the heat source needed to produce the observed geologic features.

In 2005, after one year of Enceladus observations, the Cassini spacecraft was able to detect water plumes, dust particles, and gas coming from a region near the South Pole named "Tiger Stripes", which continuously supply the tenuous E-ring (Dougherty et al., 2006; Porco et al., 2006; Waite et al., 2006; Hansen et al., 2006; Spahn et al., 2006; Schmidt et al., 2008).

Saturn's E-ring extends from 3 R_S to beyond 9 R_S (with Saturn's radius R_S = 68,268 km). It consists of sub-micron to micron-sized grains of water ice (90±1 %), CO_2 (5.3±0.1%), CH_4 (0.91±0.05%), NH_3 (0.82±0.02%), and traces of other molecules like CO, H_2 and high-order hydrocarbons (Waite et al., 2009). Horanyi et al. (2012) modeled the size distribution of E-ring ice grain size. Particles of every size have a sharp peak around Enceladus' orbital position. For particles of 0.5- and 1.5-μm size, the density drop-off is sharp and it occurres close to Enceladus' orbital position. On the other hand, 1-μm particles have a sparse distribution across the Saturn system. Postberg et al. (2009) found evidence of plumes' ice grains with 0.5-2% of sodium salts component, a percentage which is possible only if plumes originate from liquid water. This discovery reinforces the hypothesis of a subsurface ocean lying beneath an icy crust (e.g. Nimmo et al., 2007, Postberg et al., 2009), whose thickness may vary, according to temperature's variation, from tens of meters where $T \geq 100$ K to hundreds of meters for T = ~80-100 K (Matson et al., 2012).

The mechanisms allowing the plumes eruption and the source of the high heat observed on the South Polar terrains (15.8±3.1 GW, estimated by Howett et al. (2011) using Cassini/CIRS data) are still debated. The leading hypothesis is that Enceladus' main power source is the dissipation of tidal energy produced by the 2:1 resonance with Dione (Yoder, 1979; Spitale and Porco, 2006; Porco et al., 2006). The ice particles forming the E-ring pelt the surfaces of at least 11 other Saturn's satellites, including Mimas, Enceladus, Tethys, Dione and Rhea, 2007). Degruyter and Manga (2011) analyzed the relationship between particle size and distance from the vent and compared the results of their model with the results obtained by Jaumann et al. (2008) by modeling Cassini/VIMS data.

In their model, Jaumann et al. (2008) assume that Enceladus' surface is made up of pure water ice and the grains' dimension is predicted to decrease with increasing age and degree of alteration of the terrain. In particular, the Tiger Stripes region has an average particle size of 75 μm, the surrounding terrains have an average grain size between 30±10 μm and 50±15 μm, and on the old, heavily cratered terrains, 75% of all particles are calculated to be smaller 7.5 μm. For small distances from the Tiger Stripes cracks, the models by Jaumann et al. (2008) and Degruyter and Manga (2011) provide consistent results, even though these studies were conducted before the spectral effects of diffraction from sub-micron particles were known; sub-micron spectral effects were first published by Clark *et al.*, 2012). For distances >10 km from the vents, the grain size values predicted by Jaumann et al. (2008) are much larger than those suggested by Degruyter and Manga (2011)'s simulation.

A similar discrepancy is also observed with respect to Kempf et al. (2010)' simulation of plume deposits on Enceladus' surface. They predict a deposition range between 0.5 mm/year on the Tiger Stripes, closer to the vents, and 10^{-5} mm/year at the equator. Grain size values retrieved by Jaumann et al. (2008) are then possible only if the grains' growth time scale is shorter (i.e., they grow faster) than the deposition time scale.

The analysis of the infrared spectrum of Enceladus, carried out by both ground-based instrumentation (Fink et al., 1976; Clark et al., 1984; Farley, 1995; Cruikshank et al., 1998; Grundy et al., 1999; Cruikshank et al., 2005; Verbiscer et al., 2006) and on the basis of in-flight data returned by Cassini/VIMS (Brown et al., 2006), revealed a surface composed mostly by pure and crystalline water ice, with minor traces of CO_2 in the Tiger Stripes (Brown et al., 2006). Daytime surface temperatures had been shown to vary smoothly across the surface, and to be overall lower than ~90 K (Filacchione et al., 2016). The presence of ammonia or ammonia hydrate was speculated by several spectral model simulations (e.g. Verbiscer et al., 2006), but no clear evidence has emerged neither from the analysis of VIMS data, nor from ground-based observations.

The lack of ammonia could be explained by the experiments carried out by Bergantini et al. (2014). They bombarded an ice mixture of H_2O, CO_2, CH_4, NH_3, and CH_3OH at 20±2 K with 1-keV electrons to understand which processes take place and which complex species are produced or depleted. The ice composition and the temperature value were chosen to simulate Enceladus' North Pole, which is bombarded by ionizing radiation (electrons, UV and X-ray radiation, cosmic rays) coming mostly from Saturn's magnetosphere. Bergantini et al. (2014) observed from the experiment's result that H_2O has the lowest destruction rate, while NH_3 has the highest.

The variations observed in the near infrared (NIR) range 0.9-5.1 μm in VIMS data are connected not only with a gradient in composition, but also with a variation in particle size dimension (e.g. Clark and Lucey, 1984). In general, the main water ice absorption bands get deeper as the particle size increases. Since Enceladus' surface is composed mostly by pure, crystalline water ice, the grain size variation's contribution is particularly important (Jaumann et al., 2008).

When the dimension of the ice grains is smaller than some microns, new effects in the water ice spectral features arise, induced by Rayleigh scattering inside particles. Clark et al. (2008) and Clark et al. (2012) invoked the presence of sub-micron ice particles on the surface of Dione and Iapetus respectively by noticing a variation in the shape and minimum position of the 2-μm absorption band as well as spectral changes in relative band depts and IR spectral slopes.

Sub-micron ice particles can originate from the gardening processes taking place on Enceladus surface and/or from the re-deposit of plumes and E-ring micron and sub-micron ice particles. Incoming energetic particles and photons modify the surface structure and chemical composition by ionizing, exciting and breaking up water ice molecules (e.g. Baragiola et al., 2013).

In this work, we map the distribution and the abundance of sub-micron ice particles on the surface of Enceladus covered by VIMS data, and we look for a possible correlation with plume deposits predicted by Kempf et al. (2010). We do not focus on the calculation of surface physical quantities, like particle grain size or composition (i.e., materials other than water ice). Rather, our maps are intended to understand the variation of important spectral quantities (water ice absorption bands, and submicron ice particles) on a global scale. In the second part we focus on Enceladus' South Pole Terrains (SPT). In this region, some terrains were proved to display an unusual photometric behavior, namely albedo decreasing with decreasing phase angle (Schenk et al., 2014), as opposed to Tiger Stripes that do not show this effect.

3 Data selection and analysis

The Cassini Orbiter spacecraft performed 22 targeted flybys of Enceladus. In this work, we have selected and analyzed data returned by the Visual and Infrared Mapping Spectrometer (VIMS) onboard the Cassini Orbiter in some of these opportunities. VIMS is made up of two separate slit spectrometers, or channels: the Visible channel (VIMS-V) and the Infrared channel (VIMS-IR), covering the spectral ranges 0.35-1.05 μm and 0.88-5.12 μm, respectively. Here we use data from the VIMS-IR channel only. VIMS-IR spectra are sampled in 256 spectral channels, with an average spectral sampling of 16.6 nm (Brown et al., 2004; McCord et al., 2004). Data acquired by VIMS are three-indices hyperspectral images, with two spatial dimensions and one spectral dimension, commonly referred to as 'cubes'.

In this work, we selected a total of 352 cubes acquired by VIMS-IR under a solar phase angle ranging between 10° and 50°. Saturation may affect VIMS data in the infrared spectral region between 0.8 and 3 μm when high IR exposure times are applied. Since our goal is to characterize variations of the main water ice absorption bands and of the sub-micron ice grains spectral features at the best possible conditions, to improve previous analysis, we get rid of saturation effects by performing pixel-by-pixel selection of the spectral features to be used. In other words, for each VIMS pixel within our dataset, only the portion of the spectrum unaffected by saturation is retained, allowing us to save most of the original VIMS data.

VIMS data had been calibrated by using the latest radiometric response function "RC19", which corrects the spectra for a systematic shift of VIMS wavelength with time (Clark et al., 2016).

3.1 Water ice and sub-micron ice particles

The H_2O molecule has three fundamental vibrations modes. When water is in the form of hexagonal, Ih, cubic, Ic ice, it shows overtones and combinations in the near infrared range, due to OH stretches located near 3 μm, and a H-O-H bend near 6 μm. The main overtones and combinations in the visible and near infrared ranges covered by VIMS between 0.4 and 3.0 μm are located at: 0.8, 0.9, 1.04, 1.25, 1.5, and 2.0 μm.

The depth of water ice’s diagnostic absorption features is dictated by two parameters, at first order: abundance and grain size. When water ice is mixed with a contaminant material, the depth of the absorption features decreases: the higher the abundance, the deeper the absorption bands. On the other hand, the effect of grain size is bounded with surface scattering. Two types of scattering exist. In the case of surface scattering, light is reflected by the surface's grains with little (none in the ideal case) internal reflections. If the size of the grains is substantially larger than the radiation wavelength (internal or volume scattering), then photons may be refracted inside the medium and scattered or reflected back out (Hapke et al., 1978). The intensity of scattered light depends on the grain dimension. As the size of the regolith grains increases, then the greater the path the photons travel, the deeper the absorption band (Clark et al., 2011), because more radiation is absorbed. As a result, water ice absorption bands become deeper as the grain size increases, at least until first-surface reflections dominate and the band is considered saturated (Clark and Lucey, 1984).

To have a detailed description of the effects induced in the scattering mechanisms by particles of different size, the reader can refer to Zubko et al. (2013), Petrov et al. (2011; 2012), Grynko et al. (2013), and Shkuratov et al. (1999).

In this work we considered the water ice absorption bands in the IR range located at 1.25, 1.5 and 2 μm, and the reflectance peak at 3.6 μm (Figure 1). In the ideal condition of a contaminants-free surface, the intensity of the 3.6-μm reflectance peak is an indicator of grain size: the stronger the intensity of this peak, the smaller the grains (Hansen and McCord, 2004; Jaumann et al., 2008; Filacchione et al., 2012), except when sub-micron ice grains are present, then the reflectance is suppressed (Clark et al., 2012).

The reflectance value for a VIMS hyperspectral cube, characterized by some values of samples (*s*), bands (*b*), and lines (*l*), is calculated following equations in Clark et al. (2016).

The band depth values are calculated according to Clark and Roush (1984):

$$D = 1-(R_b/R_c) \quad (2)$$

where R_b is the reflectance value at the band bottom and R_c is the spectral continuum value measured at the same wavelength. R_c is found through a linear fit between the left and right wings of each band. The wavelengths and VIMS spectral channels (SC) values selected for the band's wings are:

- λ=1.163 μm and 1.376 μm (SCs 18 and 31) for the 1.25-μm band
- λ=1.376 μm and 1.804 μm (SCs 31 and 57) for the 1.5-μm band
- λ=1.804 μm and 2.232 μm (SCs 57 and 83) for the 2-μm band

The intensity of the 3.6-μm peak is evaluated by considering the maximum value of the reflectance between λ=3.512 μm (SC 160) and λ=3.682 μm (SC 170).

As mentioned in the Introduction, on the surface of Enceladus, ice grains can be smaller than 1 μm. This kind of ice particles induces peculiar effects in NIR spectra due to Rayleigh scattering, which can be used to identify them. Clark et al. (2012, 2013) listed the effects produced on the NIR spectra by sub-micron water ice particles: the 2-μm band becomes (i) asymmetric and (ii) its minimum is shifted towards longer wavelengths; (iii) the ratio between the band depths at 1.5 and 2 μm decreases; (iv) the height of the spectral peak at 2.6 μm decreases; (v) the Fresnel reflection peak at 3.1 μm is suppressed; (vi) the reflection peak at 5 μm decreases relative to the peak at 3.6 μm.

The asymmetry and minimum shift of the water ice absorption band centered at 2.02 μm was calculated by following Clark et al. (1987). As a first step, we isolate the 2.02 μm band and we remove the continuum (Figure 2). Then, a line between the two maxima shoulders is traced. The positions of the maxima and of the band's minimum value are used to fit a parabola, whose center is now considered as the band center (BC). A segment (S_1) is traced between the BC and the continuum, parallel to the y-axes. Another segment (S_2), parallel to the x-axes, is traced from the middle point (FWHM) of S_1. S_2 intercepts the absorption band in two points, S_l and S_r, on the left and on the right with respect to BD, respectively. We finally define the asymmetry as the ratio between two sub-segments: the first from S_l and the BC position (x_l), the second from the BC position and S_r (x_r). A ratio value of 1 indicates that the band is perfectly symmetric with respect to the BC position. A ratio value greater than 1 means that the left shoulder is more shifted from the BC position than the right shoulder, and vice versa for a ratio value less than 1. Since sub-micron particles make the 2.02 μm band to shift to longer wavelength values, the asymmetry observed in the 2.02 μm band is here considered to be induced by Rayleigh scattering if its value is greater than 1.

The shift in minimum position is considered with respect to λ= 2.02 μm.

The decrease of the 2.6-μm peak was estimated by performing a linear fit between the continuum level at λ=2.23 μm (SC 83) and the peak position at λ=2.581 μm (SC 104), and then considering the line slope variation.

The suppression of the Fresnel's reflection peak was estimated by considering the maximum value of the reflectance between at λ=3.029 μm (SC 131) and λ=3.179 μm (SC 140). Finally, we calculated the slope of the linear fit between λ=3.596 μm (SC 165) and λ=5.005 μm (SC 249) to infer the decrease of the reflection peak at 5 μm relative to the one at 3.6 μm.

[FIGURE 1]

[FIGURE 2]

4 Mapping spectral features

To understand how the spectral indices described in the previous section change across the surface of Enceladus, we have built spatially-resolved maps of the spectral indices. This allows us to gather a comprehensive view of the distribution of the abundance of the water ice and/or of the variation of the grain size, from sub-micron to micron-sized particles. These results will be compared with the plumes' deposits in Section 5. The maps are in cylindrical projection, and in orthographic projection for the Southern Polar Region. Each map is sampled by using a fixed-resolution grid with angular bins of 1° lat x 1° lon. Within each bin, we average the values of the spectral indices computed on the basis of all VIMS data covering that particular bin. Geometry calculations have been performed for every VIMS pixel by using the SPICE kernels and libraries provided by the NASA's Navigation and Ancillary Information Facility (Acton, 1996).

4.1 Water ice

Figure 3 maps the variation of water ice spectral signatures across the surface of Enceladus: specifically, panel *a* represents the 1.25-μm band depth, panel *b* reveals the 1.5-μm band depth, panel *c* displays the 2-μm band depth, and panel *d* accounts for the strength of the 3.6-μm reflectance peak.

The largest values of BD are observed in the Tiger Stripes and in surrounding terrains. Terrains with the lowest BD values are located between 0°W and 45°W, between 315°W and 360°W, and around 180°W. Overall, the depth of the water ice absorption bands shows a latitudinal rather than longitudinal trend, except the SPT. A regional bright spot shows up in the leading side, centered at about 90°W and 30°N. This feature is not related to any obvious morphological structure. Jaumann et al. (2008) showed the variation of the 1.50 μm BD for some Enceladus' cubes Their data cover a portion of surface spanning from 160°W to 280°W, including the Tiger Stripes region. The BD value reported by the authors, and their variation across the surface, are consistent with those calculated in this work.

The strength of the 3.6-μm reflectance peak also shows a trend across the surface, even though the VIMS coverage is not complete. This region of the spectrum can be indeed very noisy. The region corresponding to the abovementioned bright spot has relatively high 3.6-μm peak values, while this spectral index decreases to background levels moving towards 0°W and 180°W. The lowest values in the 3.6-μm reflectance peak are recorded in the Tiger Stripes, indicating that the grain size in this region is bigger than in the rest of the surface or there is a significant component of sub-micron ice grains. Spectral markers of water ice mapped across the surface of Enceladus are ultimately related to a variation in grain size rather than in composition.

[FIGURE 3]

4.2 Sub-micron ice particles

Figure 4 shows the variation of several spectral markers indicative of sub-micron ice grains. Panels *a* and *b* represent the asymmetry and the minimum position for the 2-μm band, respectively.

The value of the parameter marking the asymmetry, is almost everywhere close, or slightly above, 1, meaning that the band at 2.02 μm is quite symmetric across the whole Enceladus' surface. The position of the minimum is centered at the reference position of 2.02 μm.

On the SPT the asymmetry parameter's value is below unity. Therefore, this region has an asymmetric 2.02 μm band, and its minimum shows a shift toward shorter wavelength. On the other hand, sub-micron ice particles make the 2.02 μm band to shift longward. We can conclude that the observed shift is not connected with sub-micron ice particles. A closer inspection of the two maps shows that the 2-μm band is more asymmetric in data covering the leading hemisphere than in data covering the trailing hemisphere. The same behavior is observed in Figure 4*b* for the minimum position. These two maps ultimately reveal that the SPT host the lowest amount of sub-micron ice particles. Their abundance may be slightly higher in the rest of the surface, mostly on the leading hemisphere.

The ratio between the BD at 1.50 μm and 2.02 μm is shown in Figure 4*c*. The Tiger Stripes are very well defined and constrained in the cylindrical and orthographic maps. They show the highest value of this ratio, indicating that the amount of sub-micron particles in this region is the lowest across the entire surface. Conversely, the regions comprised between 0°-45°W, 315-360°W, and around 180°W, have the highest concentration of sub-micron ice particles. The bright spot centered at 30°N, 90°W shows up again in this band ratio map. Trends hitherto described for Figure 4*c* are largely confirmed in Figure 4*d* as far as the variation in the strength of the 2.60-μm reflectance peak is concerned.

The last two maps represented in Figures 4*e* and 4*f,* respectively display the variation in the strength of the 3.1-μm Fresnel peak and in the 5.0/3.6-μm reflectance peaks' ratio. Both these spectral indices show a subtle variation across the surface. In Figure 4*e*, the 3.1-μm Fresnel peak is stronger in and around the Tiger Stripes, as opposed to the leading hemisphere where it is generally weak. The value of the 5.0/3.6-μm slope in Figure 4*f* increases in moving away from the leading hemisphere to the trailing hemisphere, being maximum in the SPT. These maps confirm previous results, in that the Tiger Stripes and the SPT show the least abundance of sub-micron particles, while their amount increases in the rest of the surface, particularly on the leading side.

[FIGURE 4]

5 Plume's deposits

The material ejected from Enceladus' South Polar fractures is composed primarily by water ice in variable grain sizes. Most of the ejecta redeposit on the surface with a rate simulated by Kempf et al. (2010) to be 0.5 mm/yr close to the vents, and 10^{-5} mm/year at the equator. Results of these simulations are represented in graphic form in Figure 5, where it can be easily observed that the deposition rate decreases with increasing distance from the Tiger Stripes: The plumes' deposits are broad below 45°S, then they split into two patterns centered at ~45°W and ~205°W, respectively.

We show here a comparison between the results described in Sections 2 and 3 by analyzing VIMS data, and the plumes' deposits model. In our analysis we also considered the four global, high spatial resolution colored maps, produced by Schenk et al. (2011) by cylindrically projecting and mosaicking ISS data in the IR3 (0.930 μm), GRN (0.586 μm) and UV3 (0.338 μm) filters. In this way, we gather a comprehensive view of the plumes' pattern in a broader spectral range.

[FIGURE 5]

To visualize the re-deposition processes taking place on the surface of Enceladus, we extracted level curves from Figure 5 overlapping them on top of VIMS-derived maps described before. The results are shown in Figure 6.

The water ice distribution maps (panels: 6*a*, 6*b*, and 6*c*) show overall a good agreement with the predicted ejecta deposits in the SPT and in the eastern portion of the trailing hemisphere. The model predicted the ice to deposit along a band centered at ~205° W on the trailing hemisphere (Figure 5). This theoretical pattern is in fact reproduced by color changes observed in our maps, in the longitude range from 135°W to 205°W, corresponding to larger values of the depth of water ice absorption bands. Indeed, we expect to observe deeper absorptions where the plumes' deposition rate increases, since the ice particles' size of the ejecta falling back on the surface decreases with increasing distance from the ejecta source (Degruyter and Manga, 2011; Kempf et al., 2010). From 205°W to 360°W, the match between the model and the data is more elusive.

On the leading side, the maps and the plumes deposits' prediction diverge. The regional bright spot centered at 30°N, 90°W is a distinct feature, hardly connected to any ejecta coming from the Southern Polar region, since the model predicts deposits to be negligible in this region. More generally, the predicted deposits' pattern centered at 45°W (see Figure 5) does not match at all the variations observed in water ice absorption bands. Both the ejecta deposition rate and the water ice BDs show a latitudinal trend on the leading hemisphere, but their positions in longitude do not overlap.

The 1.50/2.02 μm BD ratio in Figure 6*d* totally reproduces the water ice BDs behavior. The portion of Enceladus' surface richer in sub-micron ice particles corresponds to terrains where the plumes' deposition rate is minimum.

Figure 6*e* and 6*f* show a comparison between the plumes' model and the variation in the asymmetry and minimum position of the 2-μm water ice band, respectively. We again observe no match between the model and VIMS data, since the values of these two parameters show a very light change across Enceladus' surface. On the SPTs, VIMS data and the theoretical model show a higher agreement.

To sum up, then, we notice that terrains where the plumes deposition rate is higher (SPTs), lack in submicron particles. As deposits rate fades away, submicron particles abundance increases. This may indicate a possible connection between lack of abundance of sub-micron particles and plumes' deposits.

[FIGURE 6]

ISS color maps are displayed in Figure 7. The first three panels show three ratio maps: GRN/UV3 (Figure 7a), IR3/GRN (Figure 7b), and IR3/UV3 (Figure 7c). The last panel represents the RGB combination of the three filters. In the GRN/UV3, IR3/GRN, and IR3/UV color ratio maps, bright areas are associated with a positive slope relative to the ratioed bands. The bright regions in the GRN/UV3, IR/UV3, and RGB combination resemble the plumes outlined in the deposits model. The IR3/GRN map is smoother and does not resemble ejecta deposits. The bright region in the leading hemisphere, observed in the water ice band depths maps, is clearly visible in the GRN/UV3 map. In the IR3/UV3 and in the RGB combination it is still visible although less contrasted, while it disappears in the IR3/GRN. The maximum brightness's position, however, seems to be shifted southward compared to the water ice BD maps.

[FIGURE 7]

6 South Polar Terrains

Terrains closer to the Tiger Stripes show a peculiar behavior with changing illumination conditions (Schenk et al., 2014). In Figure 8 we report two different images of the same region of Enceladus. The left panel shows a mosaic of ISS images of SPT acquired at phase angles ranging from 0° to 10°, while in the right panel the range is 10°-40°. In the left-hand image, some terrains located north of the Tiger Stripes appear to have a lower albedo (i.e., are darker) than in the right-hand image. Another dark spot observed only in the left map is located south-east of the Tiger Stripes. The two images are again a RGB combination of the UV3, GRN, and IR3 ISS filters. Generally, the albedo or the reflectance value of an atmosphereless object' surface shows a steep, non-linear increase due to the opposition effect when the phase angle drops below 10° (e.g., Pitman et al., 2010; Verbiscer et al., 2005). In this case, then, these two portions of Enceladus' surface have an opposite behavior (Schenk et al., 2014).

To understand whether this phenomenon is reproduced in the infrared spectrum measured by VIMS, we divided our dataset into four intervals of phase angle values, and we created maps of spectral features covering the surface of Enceladus including its South Pole. These ranges are: 10°-20°, 20°-30°, 30°-40°, and 40°-50°. However, we did not consider the 0°-10° range, as only 3 VIMS data covering the South Pole were acquired under such observing conditions, and their spatial resolution is too coarse to safely allow one to associate the spectral parameters with any specific morphological structure.

[FIGURE 8]

Results are summarized in Figure 9. We also produced maps of the entire surface in cylindrical projection, to understand whether the results obtained for the South Pole are reliable or not.

In the orthographic maps, irregular black contours highlight the position of the two dark terrains. In Figures 9*a* and 9*b*, the value of BDs at 1.50 and 2.02 μm show some variation in the Southern Polar region as a function of the phase angle value. At low phase, the absorption bands appear to be shallower in the orthographic projection, while the Tiger Stripes retain the same BD values at all phase angles. The same is observed for the other three spectral indices. However, the position of the dark terrains in Figure 8 is only partially covered by VIMS data, or not covered at all at low phase angles. The variations in the values of the spectral indices, however, are too subtle to tell if VIMS data are consistent with ISS results. Moreover, the spectral indices show a variation with the phase angle ranges in the cylindrical maps too. Consequently, these variations are not restricted to the SPT only, but they involve the whole surface. This observation leads us to conclude that the observed variation in the spectral indices are connected with a change in the illumination conditions. The behavior observed in the ISS data and shown in Figure 8 is not confirmed by VIMS-IR observations. Since no VIMS data were acquired below 10° at useful spatial resolution, we cannot understand if this discrepancy may be override by considering small-phase angle observations, or if the change in albedo in the SPT doesn’t show up in the NIR range covered by VIMS at all.

[FIGURE 9]

7 Conclusions

We investigated the re-deposition of material erupted from Enceladus' South Pole by analyzing VIMS data acquired in the infrared range 1-5 μm. We first considered the depth of the main water ice absorption bands, and we built global maps displaying the variation of these band depth values across the surface, with a fixed angular resolution of 1 degree in both latitude and longitude. We then compared these maps with the model of plumes' deposits proposed by Kempf et al. (2010). The results show a partial overlap between VIMS data and theoretical data just on the SPT. The leading hemisphere is characterized by a regional bright (deep band depths) spot centered at about 30°N, 90°W. It is possible that this accumulation of fresh water ice, or ice with larger grain size, masks the signature of the plumes' deposits. Indeed, the predicted deposition rate in this portion of surface is very low, of the order of 10^{-5} mm/year (Kempf et al., 2010). The origin of this bright spot is unknown, since Enceladus' surface does not show any distinct morphological structure here. ISS maps show an albedo spot in this region too, mostly in the UV filter.

We then focused on the investigation of the distribution of sub-micron particles by considering six spectral indices. Our analysis demonstrates that those terrains showing the deepest water ice absorption bands correlate with the lowest amount of sub-micron particles. For a surface depleted in visually dark, non-ice contaminants, like the average surface of Enceladus, this leads to the interpretation that the variation measured in the depth of the water ice absorption bands is directly related to a variation in grain size, rather than to a compositional gradient. This conclusion is supported by the map of the variation of the strength of the reflection peak at 3.6 μm, which is also a consequence of the grain size.

The map showing the band depths ratio 1.50/2.02 μm overall show a good agreement with the predicted plumes' deposits on the trailing side, where the amount of sub-micron particles decreases with increasing accumulation of ejecta material. However, this correlation is much weaker, or even absent, on the leading side of Enceladus, where the abundance of sub-micron particles is the highest across the entire surface. The other maps for the sub-micron ice particles show a lower contrasted variation of the spectral indicators, making the conclusions uncertain.

In ISS data, some terrains surrounding the Tiger Stripes surprisingly show a suppression of the opposition surge, since their albedo decreases with decreasing phase angle, as opposed to what is commonly observed on most planetary airless surfaces. However, this behavior cannot be confirmed by the VIMS dataset available for this work in the infrared range. Indeed, almost no VIMS data were acquired in South Polar terrains with a phase angle smaller than 10°, which precludes a direct comparison with ISS data. Furthermore, the available data do not allow a complete coverage of those terrains showing this behavior for the four phase angle ranges we considered. It is unknown if near infrared spectra may display the same behavior of ISS data when the phase angle is lower than 10°.

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Figures captions

Figure 1: The main water ice combinations and overtones in the near-infrared spectral range covered by the VIMS spectrometer between 0.8 and 5.0 µm, are located at: 1.04, 1.25, 1.5, 2.0, and 3.0 µm, while a reflectance peak arises at 3.6 µm. The main spectral features connected with the presence of water ice's sub-micron particles on the surface are: the asymmetry of the 2-µm absorption band; the shift of its band center towards longer wavelengths; the decrease of the ratio between the band depths at 1.5 and 2 µm, and of the height of the spectral peak at 3.6 µm; the suppression of the Fresnel reflection peak at 3.1 µm; the decrease of the reflection peak at 5 µm relative to the peak at 3.6 µm. The position of the abovementioned diagnostic spectral features is indicated by dashed lines. The spectrum used here had been produced by averaging some pixels on the South Pole of Enceladus.

Figure 2: Sketch representing the method used here to evaluate the degree of asymmetry of the absorption band at 2 µm (Clark et al., 1987). See text for details.

Figure 3: Cylindrically-projected maps representing the variation of the depth of the 1.25 **(a)**, 1.50 **(b)**, and 2.0 **(c)** µm absorption bands, and the height of the 3.6 µm **(d)** reflection peak. The South Pole is in the orthographic-projected maps. Maps are sampled by using a fixed-resolution grid with angular bins of 1° lat x 1° lon.

Figure 4: Cylindrically-projected maps representing the variation of the main sub-micron particles spectral indicators: the asymmetry **(a)** and the shift of the minimum position **(b)** of the 2.0 µm water ice absorption band; the ratio of the BDs of the 1.50 and 2.0 µm features (**c**); the variation of the height of the peaks at 2.60 **(d),** 3.10 **(e),** and 5.0 **(f)** µm. The South Pole is in the orthographic-projected maps. Maps are sampled by using a fixed-resolution grid with angular bins of 1° lat x 1° lon.

Figure 5: Predicted distribution of the plume's deposits, simulated by Kempf et al. (2010).

Figure 6: We extracted level curves from Figure 5, and we overplotted them on the VIMS-derived maps: the absorption bands at 1.25 **(a)**, 1.50 **(b)**, and 2.0 **(c)** µm, the 1.50/2.0 µm BDs ratio **(d)**, and the asymmetry **(e)** and minimum shift **(f)** of the 2.0 µm absorption band.

Figure 7: The level curves extracted from Figure 5 had been overlapped on four global, high spatial resolution colored maps, produced by Schenk et al. (2011) by cylindrically projecting and mosaicking ISS data in the IR3 (0.930 µm), GRN (0.586 µm) and UV3 (0.338 µm) filters. The maps are GRN/UV **(a)**, IR/GRN **(b)**, IR/UV **(c)**, and the RGB combination of the three filters **(d)**.

Figure 8: From Figure 2 of Schenk et al. (2014). The **left** panel shows a mosaic of ISS images of SPT acquired at phase angles ranging from 0° to 10°, while in the **right** panel the range is 10°-40°. In the left-hand image, some terrains located north of the Tiger Stripes appear to have a lower albedo (i.e., are darker) than in the right-hand image.

Figure 9: We divided our selected VIMS observations into four ranges of phase angle values and maps of spectral features covering the surface of Enceladus including its South Pole. These ranges are: 10°-20°, 20°-30°, 30°-40°, and 40°-50°. On the orthographic-projected maps, the two solid-lined shapes indicate the position of the dark regions observed in the ISS images. The maps represent the variation of the BDs of the 1.50 **(a),** and the 2.0 **(b)** µm features, and of the 1.50/2.0 µm BDs ratio **(c)**, and the asymmetry **(d)** and minimum shift **(e)** of the 2.0 µm absorption band.

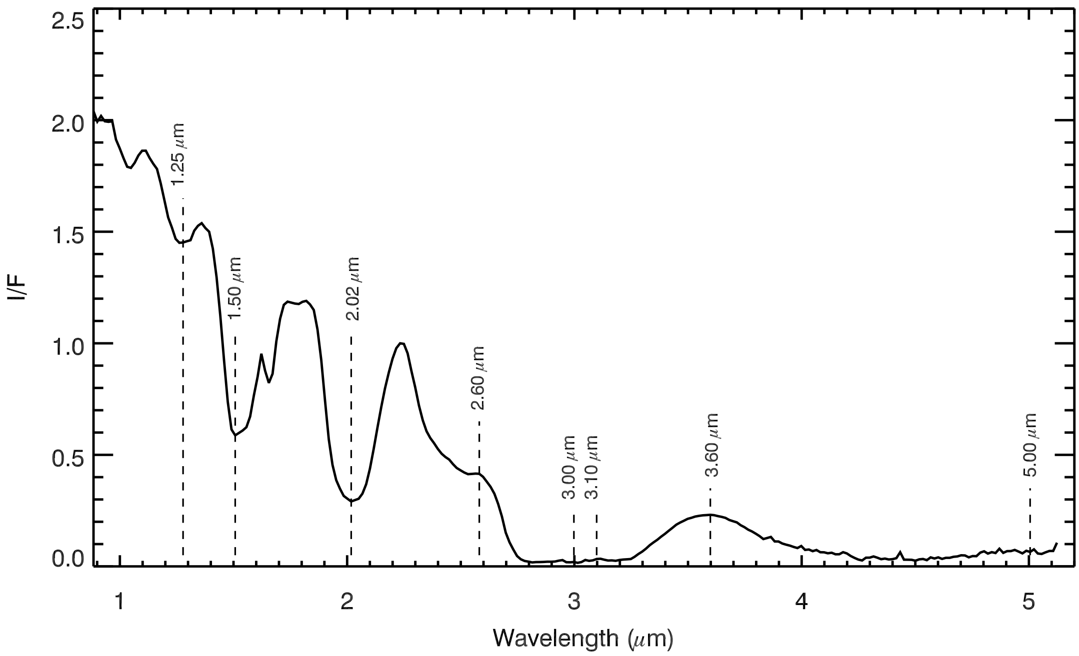


Figure 1

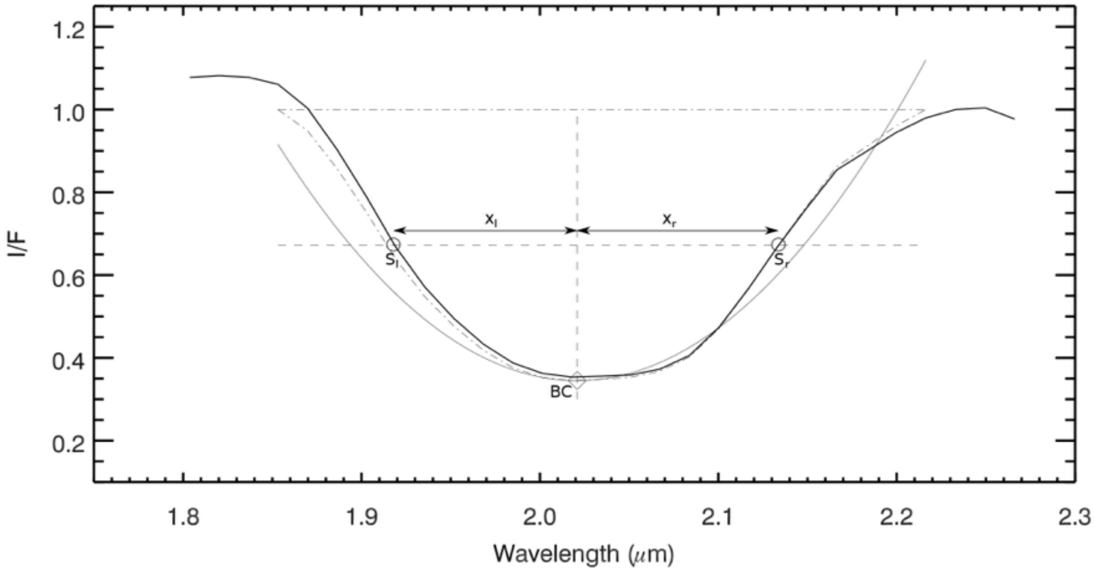
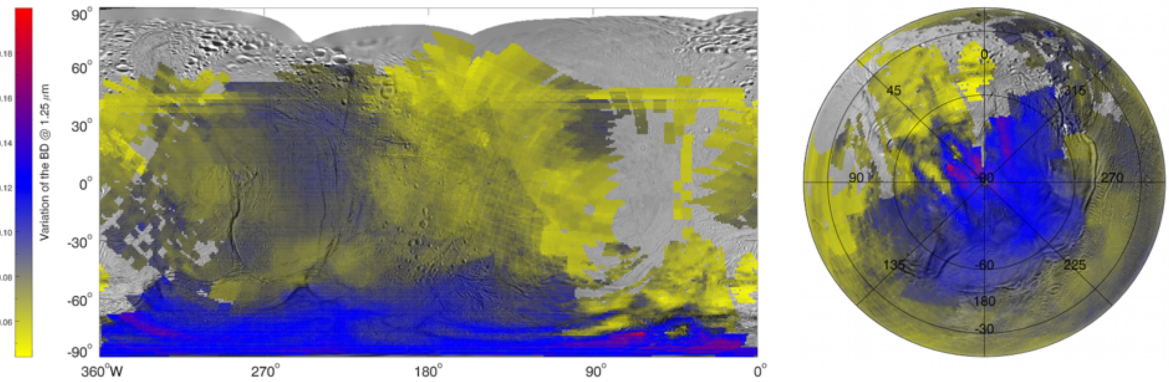
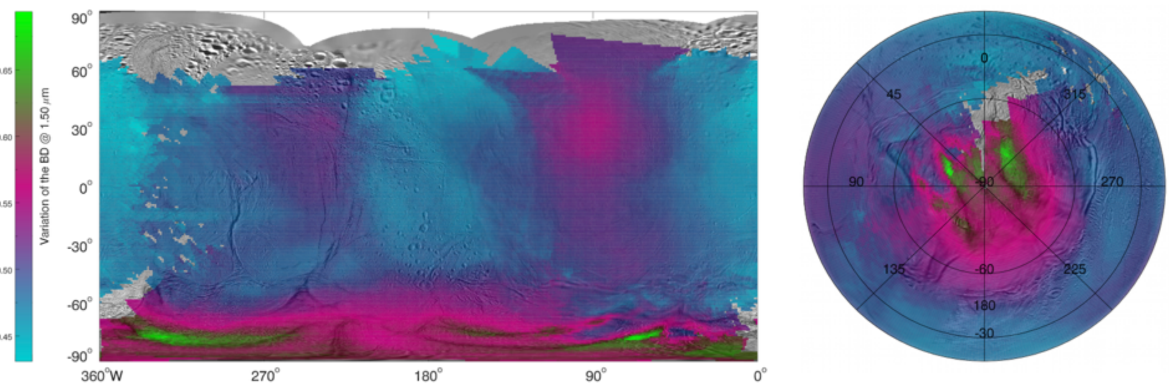


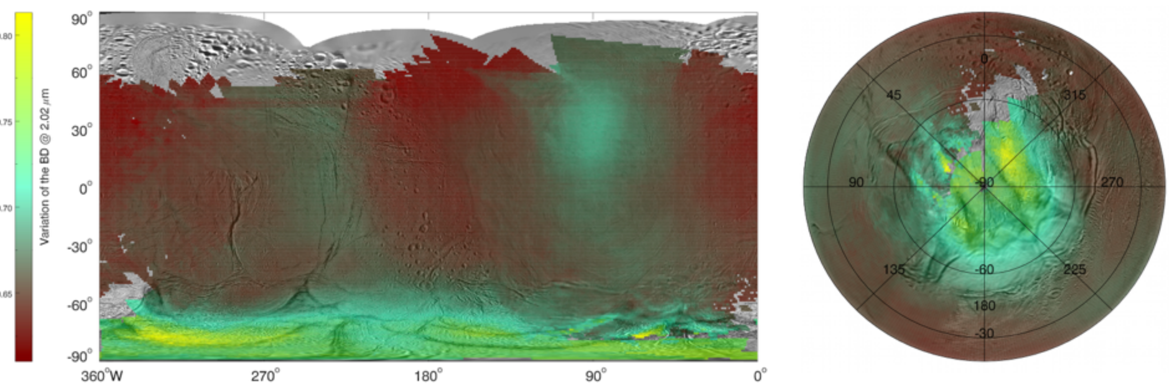
Figure 2


Variation of the BD @ 1.25 μm
0.18
0.16
0.14
0.12
0.10
0.08
0.06
90°
60°
30°
0°
-30°
-60°
-90°
360°W
270°
180°
90°
0°
0
45
315
90
-90
270
135
-60
225
180
-30

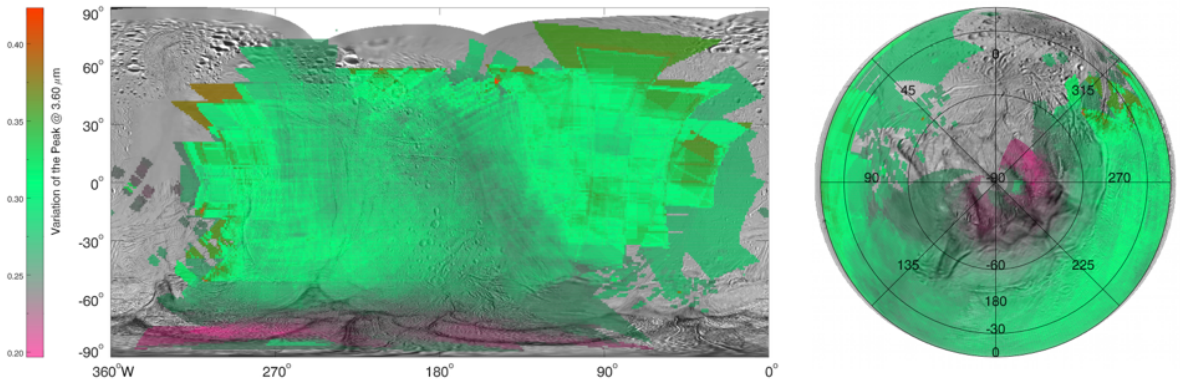
(a)


Variation of the BD @ 1.50 μm
0.65
0.60
0.55
0.50
0.45
90°
60°
30°
0°
-30°
-60°
-90°
360°W
270°
180°
90°
0°
0
45
315
90
-90
270
135
-60
225
180
-30

(b)


Variation of the BD @ 2.02 μm
0.80
0.75
0.70
0.65
90°
60°
30°
0°
-30°
-60°
-90°
360°W
270°
180°
90°
0°
0
45
315
90
-90
270
135
-60
225
180
-30

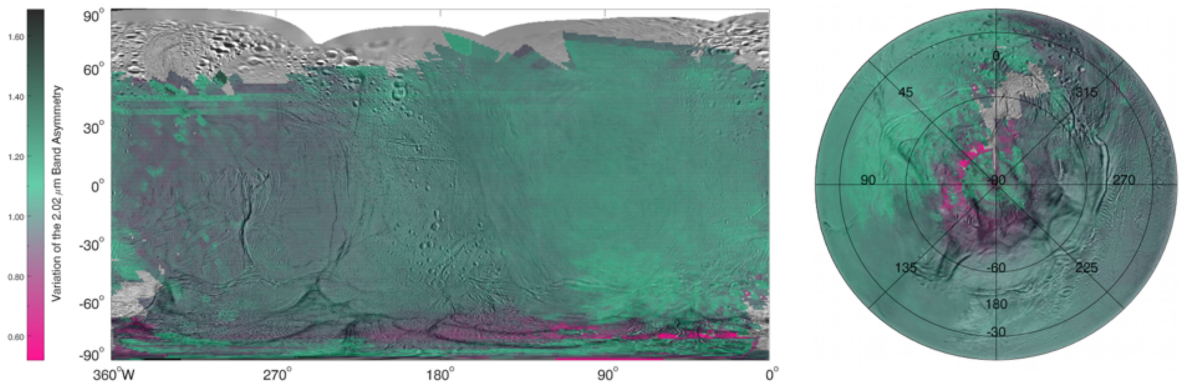
(c)



Variation of the Peak @ 3.60 μm
0.40
0.35
0.30
0.25
0.20
90°
60°
30°
0°
-30°
-60°
-90°
360°W
270°
180°
90°
0°
0
45
315
90
-90
270
135
-60
225
180
-30

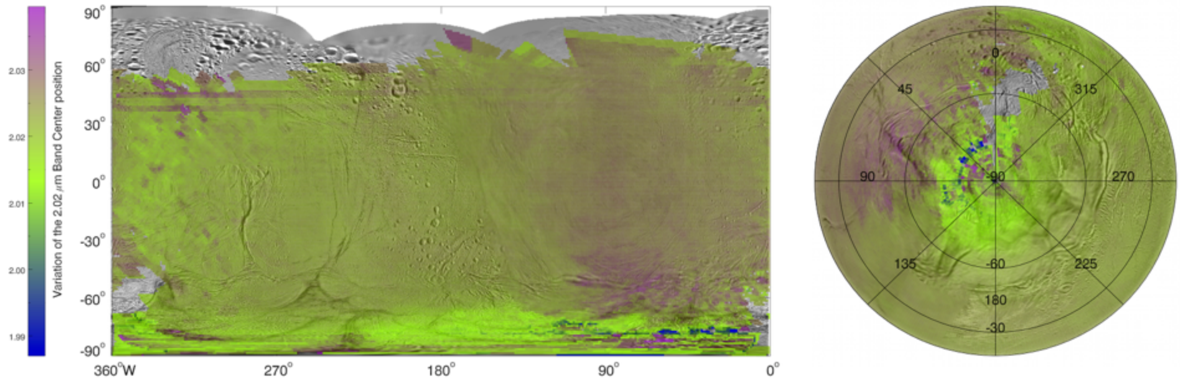
(d)

Figure 3

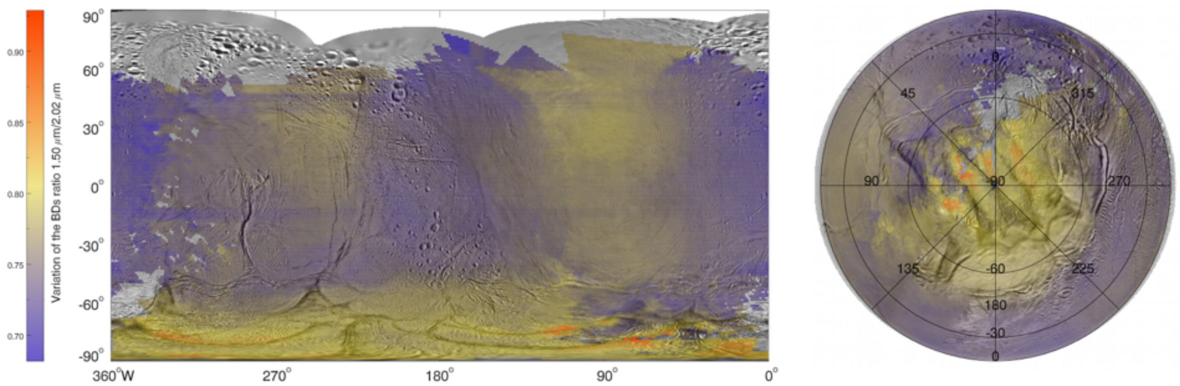


Variation of the 2.02 μm Band Asymmetry
1.60
1.40
1.20
1.00
0.80
0.60
90°
60°
30°
0°
-30°
-60°
-90°
360°W
270°
180°
90°
0°
0
45
315
90
-90
270
135
-60
225
180
-30

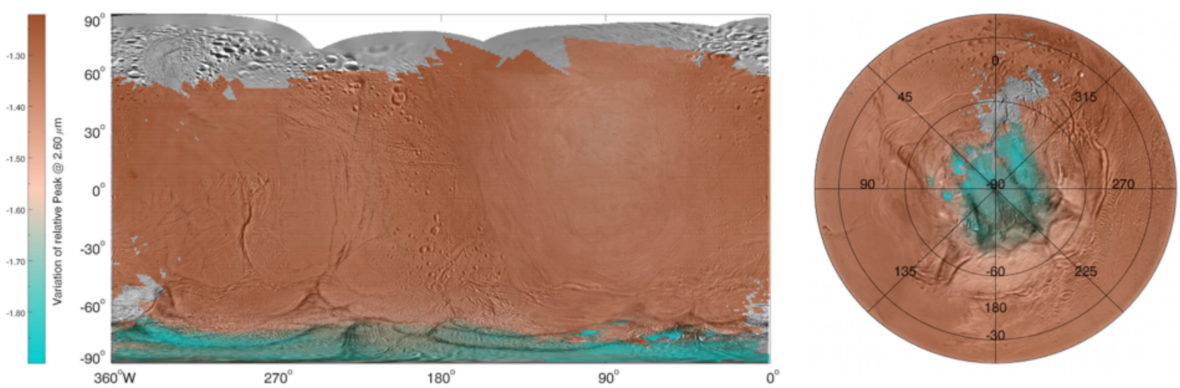
(a)


Variation of the 2.02 μm Band Center position
90° 60° 30° 0° -30° -60° -90°
360°W 270° 180° 90° 0°

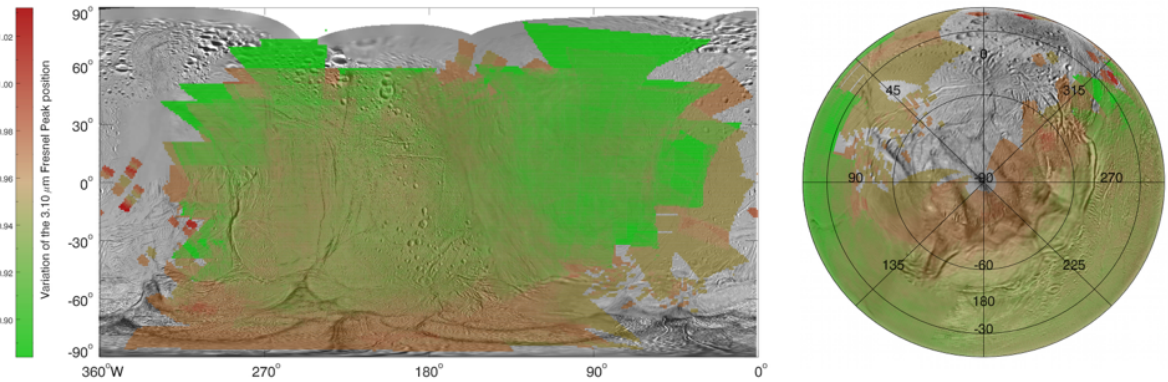
(b)


Variation of the BDs ratio 1.50 μm/2.02 μm
90° 60° 30° 0° -30° -60° -90°
360°W 270° 180° 90° 0°

(c)

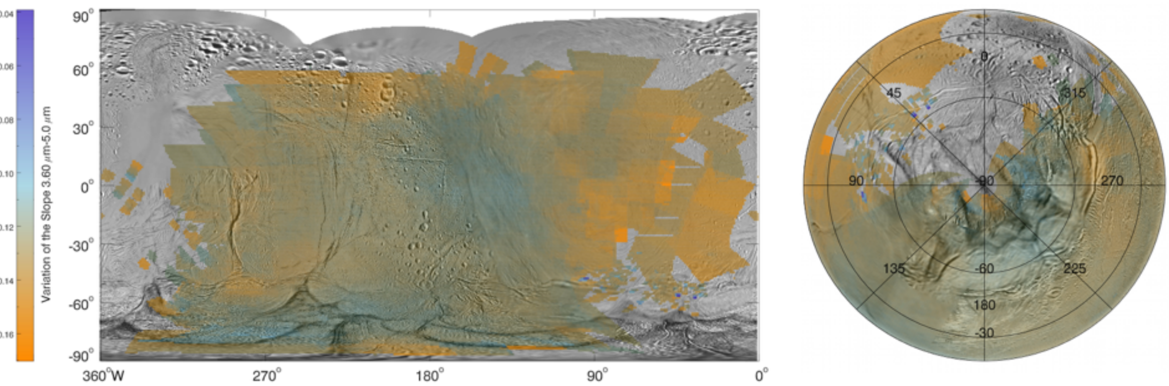

Variation of relative Peak @ 2.60 μm
90° 60° 30° 0° -30° -60° -90°
360°W 270° 180° 90° 0°

(d)



Variation of the 3.10 μm Fresnel Peak position
1.02
1.00
0.98
0.96
0.94
0.92
0.90
90°
60°
30°
0°
-30°
-60°
-90°
360°W
270°
180°
90°
0°
0
45
315
90
-90
270
135
-60
225
180
-30

(e)



Variation of the Slope 3.60 μm-5.0 μm
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
-0.16
90°
60°
30°
0°
-30°
-60°
-90°
360°W
270°
180°
90°
0°
0
45
315
90
-90
270
135
-60
225
180
-30

(f)

Figure 4

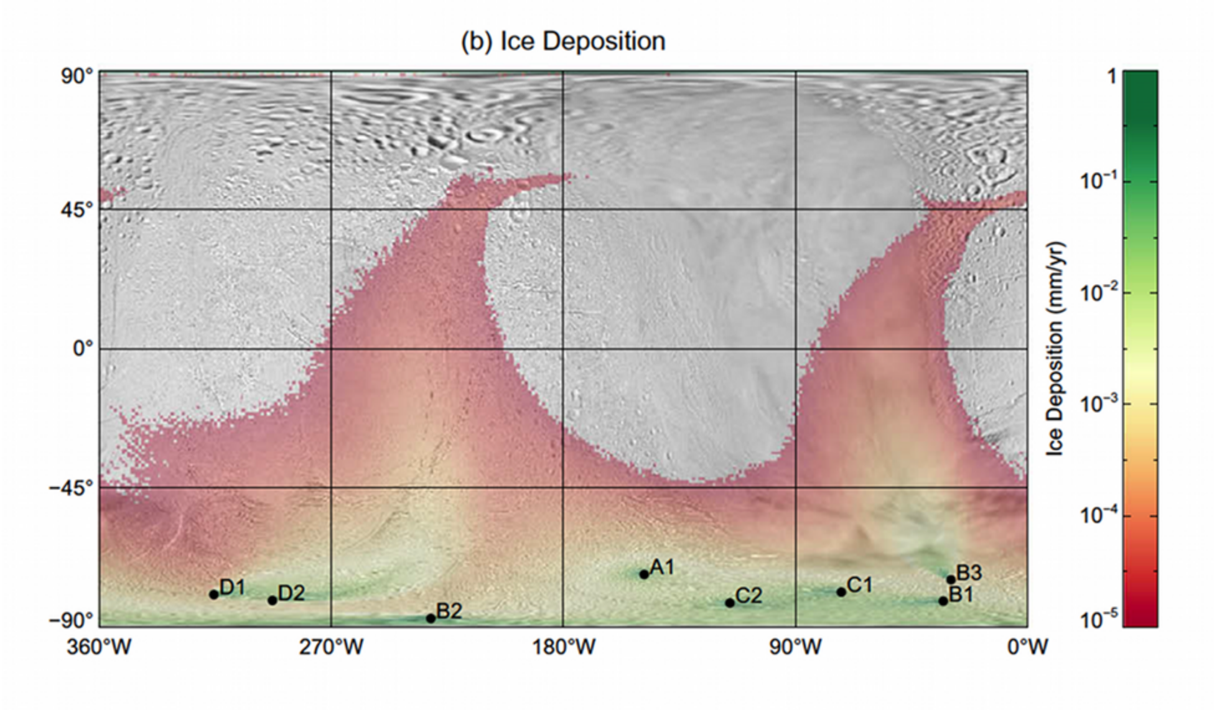
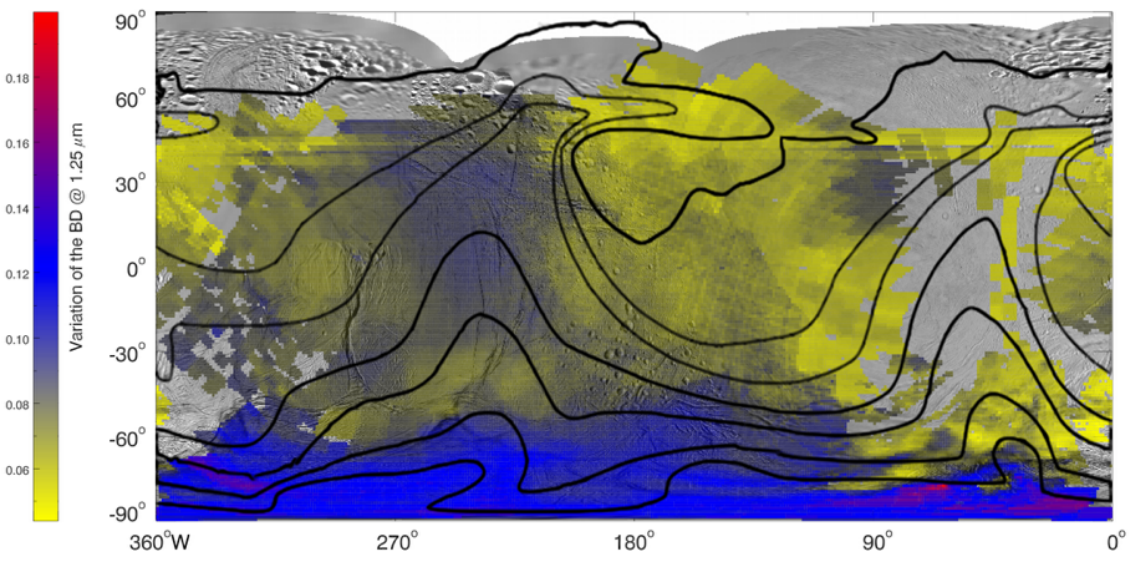
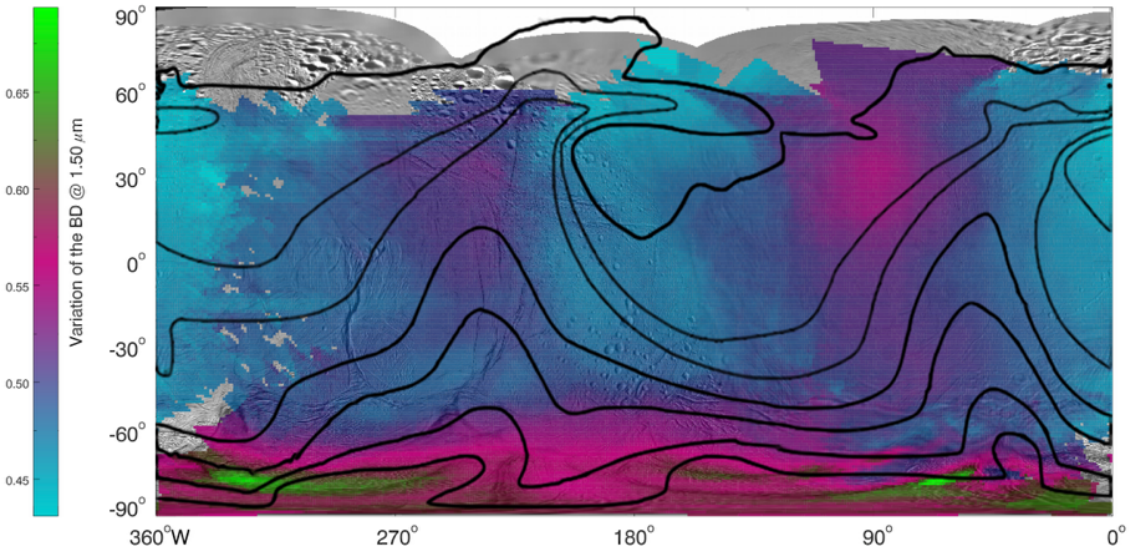

(b) Ice Deposition
90°
45°
0°
-45°
-90°
360°W
270°W
180°W
90°W
0°W
D1
D2
B2
A1
C2
C1
B3
B1
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Ice Deposition (mm/yr)

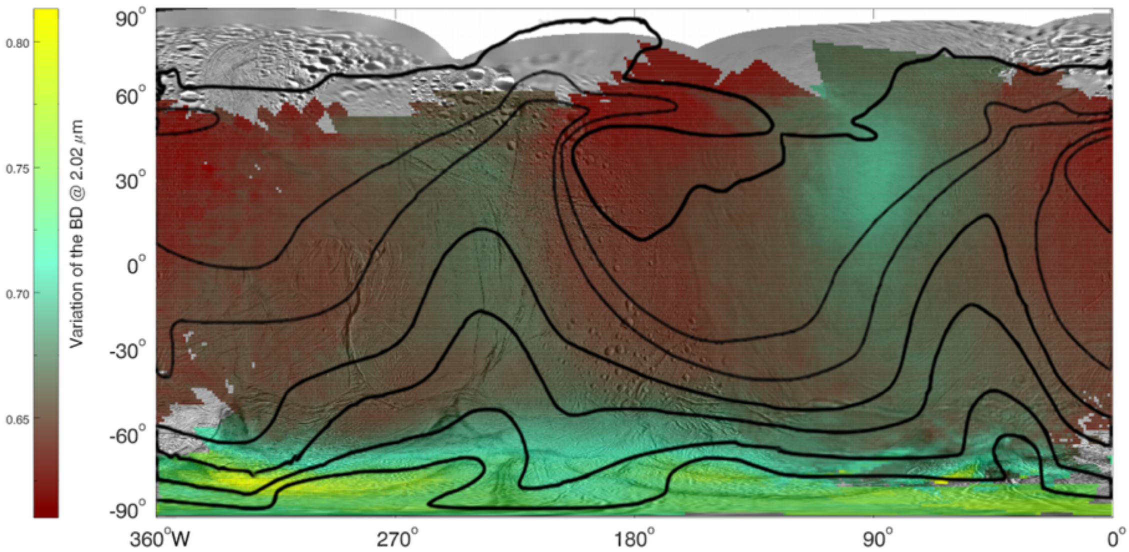
Figure 5


Variation of the BD @ 1.25 μm
0.18
0.16
0.14
0.12
0.10
0.08
0.06
90°
60°
30°
0°
-30°
-60°
-90°
360°W
270°
180°
90°
0°

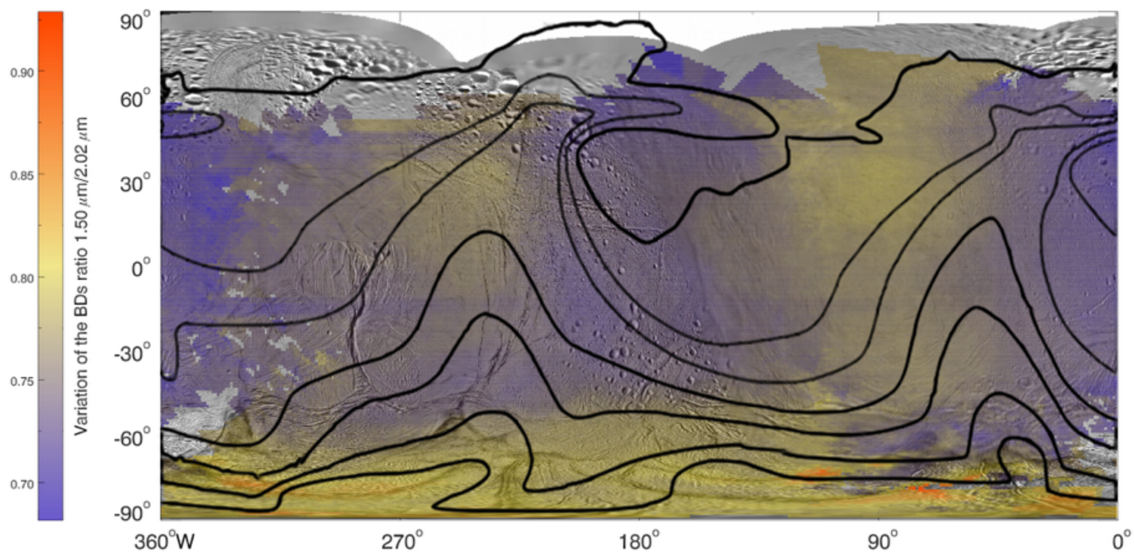
(a)


0.65
0.60
0.55
0.50
0.45
Variation of the BD @ 1.50 μm
90°
60°
30°
0°
-30°
-60°
-90°
360°W
270°
180°
90°
0°

(b)

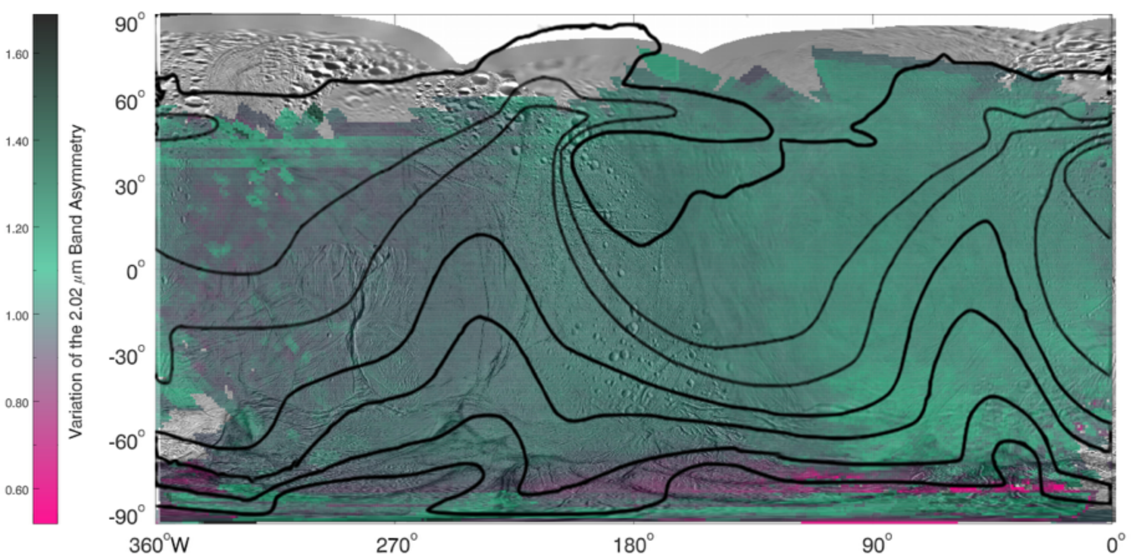

0.80
0.75
0.70
0.65
Variation of the BD @ 2.02 μm
90°
60°
30°
0°
-30°
-60°
-90°
360°W
270°
180°
90°
0°

(c)



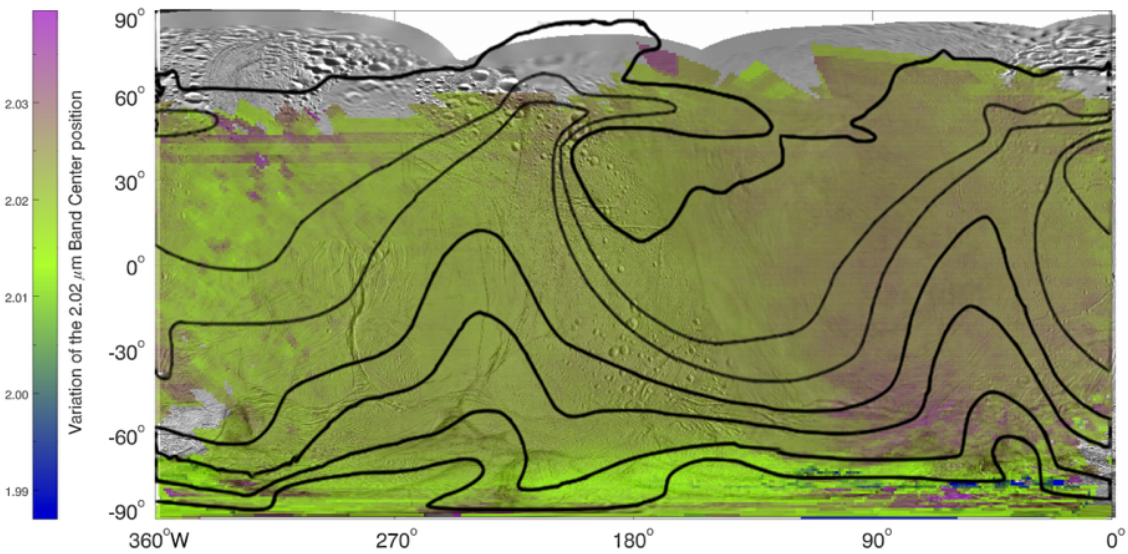
Variation of the BDs ratio 1.50 μm/2.02 μm
0.90
0.85
0.80
0.75
0.70
90°
60°
30°
0°
-30°
-60°
-90°
360°W
270°
180°
90°
0°

(d)



Variation of the 2.02 μm Band Asymmetry
1.60
1.40
1.20
1.00
0.80
0.60
90°
60°
30°
0°
-30°
-60°
-90°
360°W
270°
180°
90°
0°

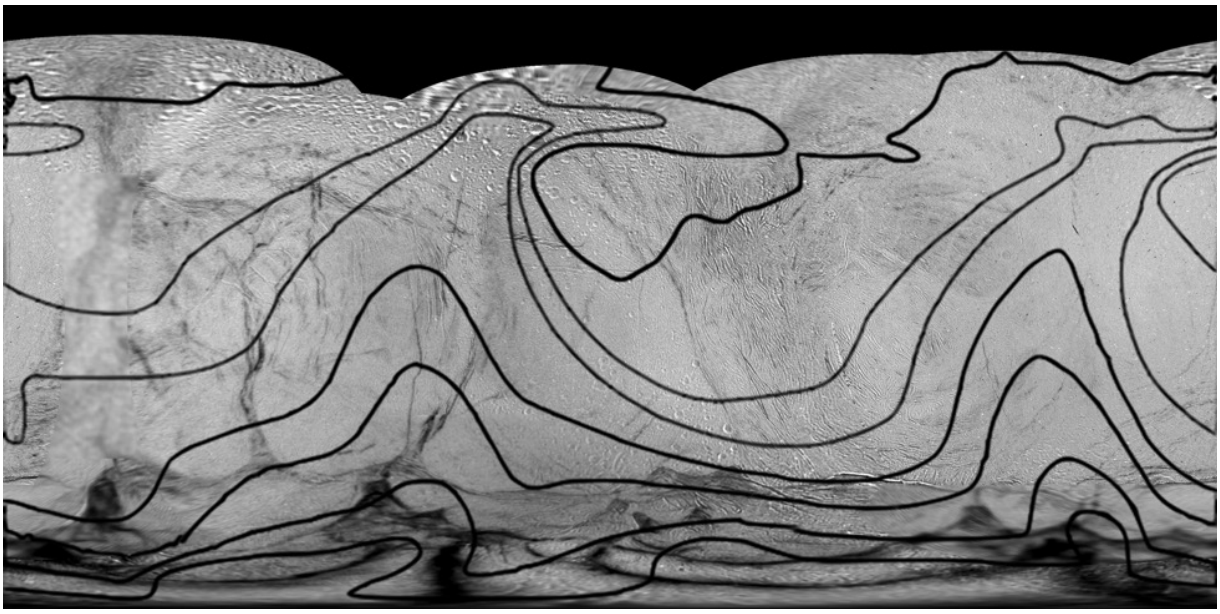
(e)


Variation of the 2.02 μm Band Center position
2.03
2.02
2.01
2.00
1.99
90°
60°
30°
0°
-30°
-60°
-90°
360°W
270°
180°
90°
0°

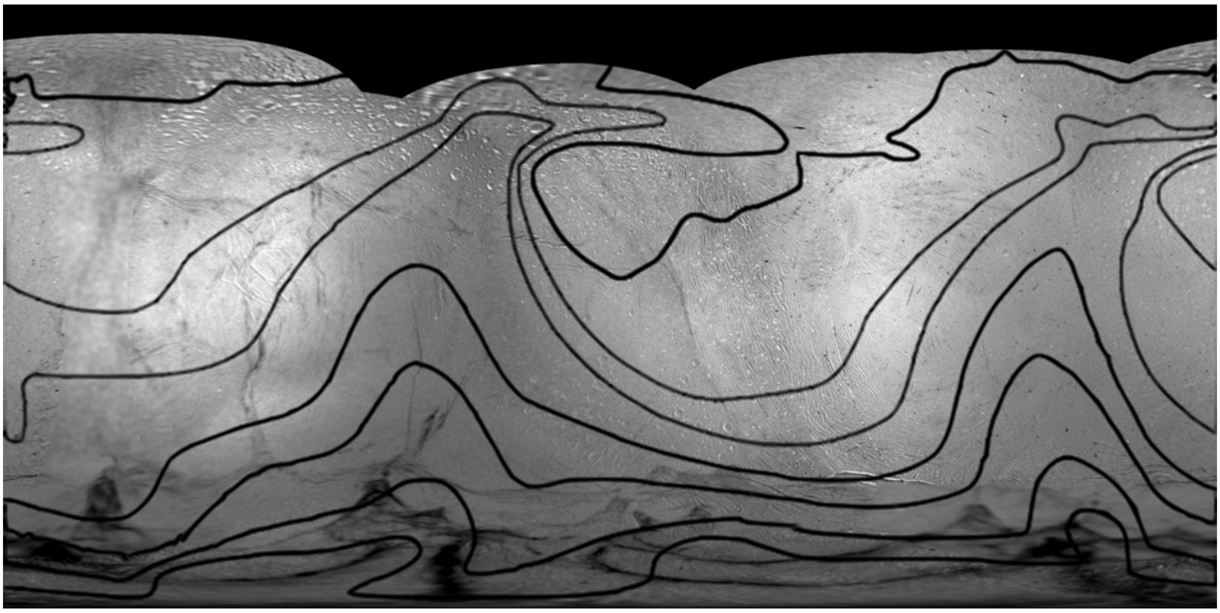
(f)

Figure 6

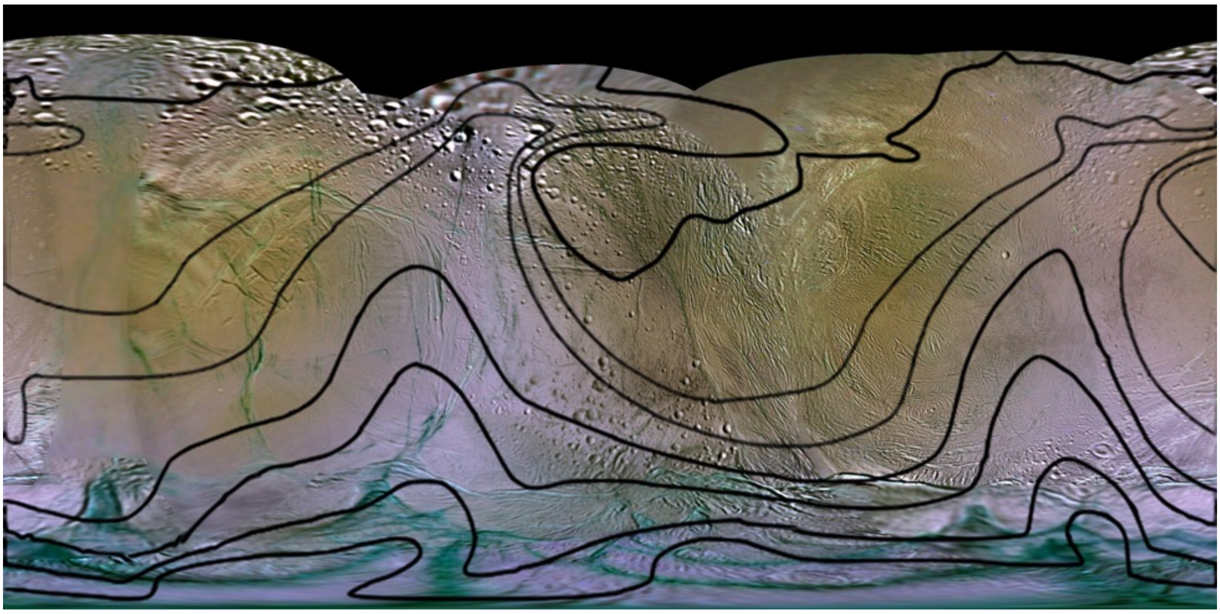
(a)



(b)



(c)



(d)

Figure 7

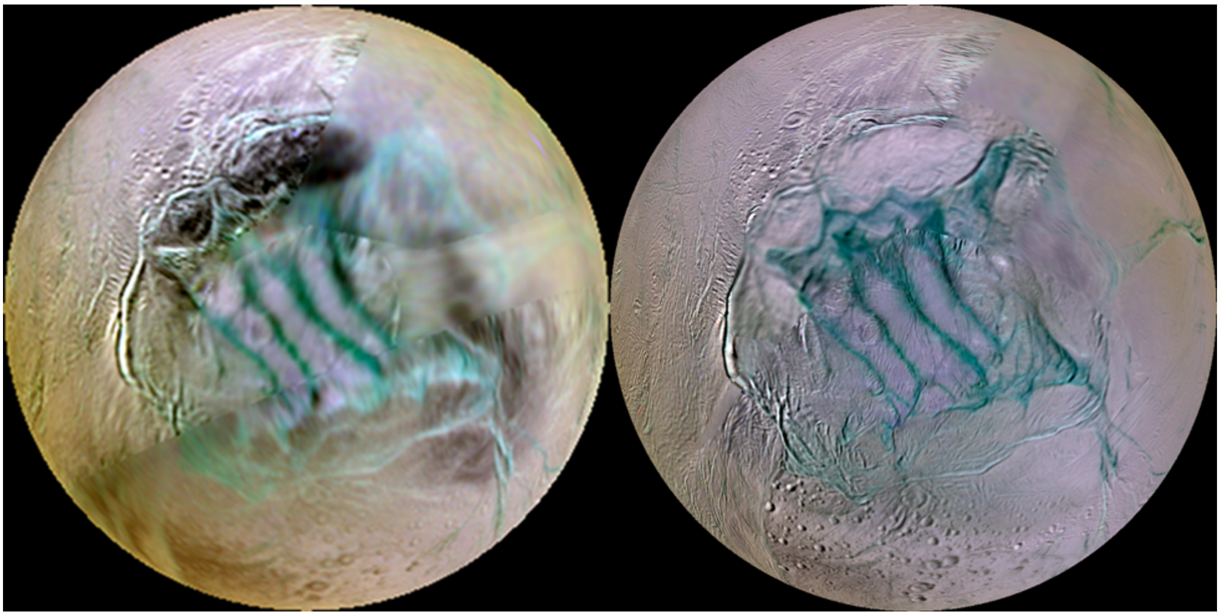
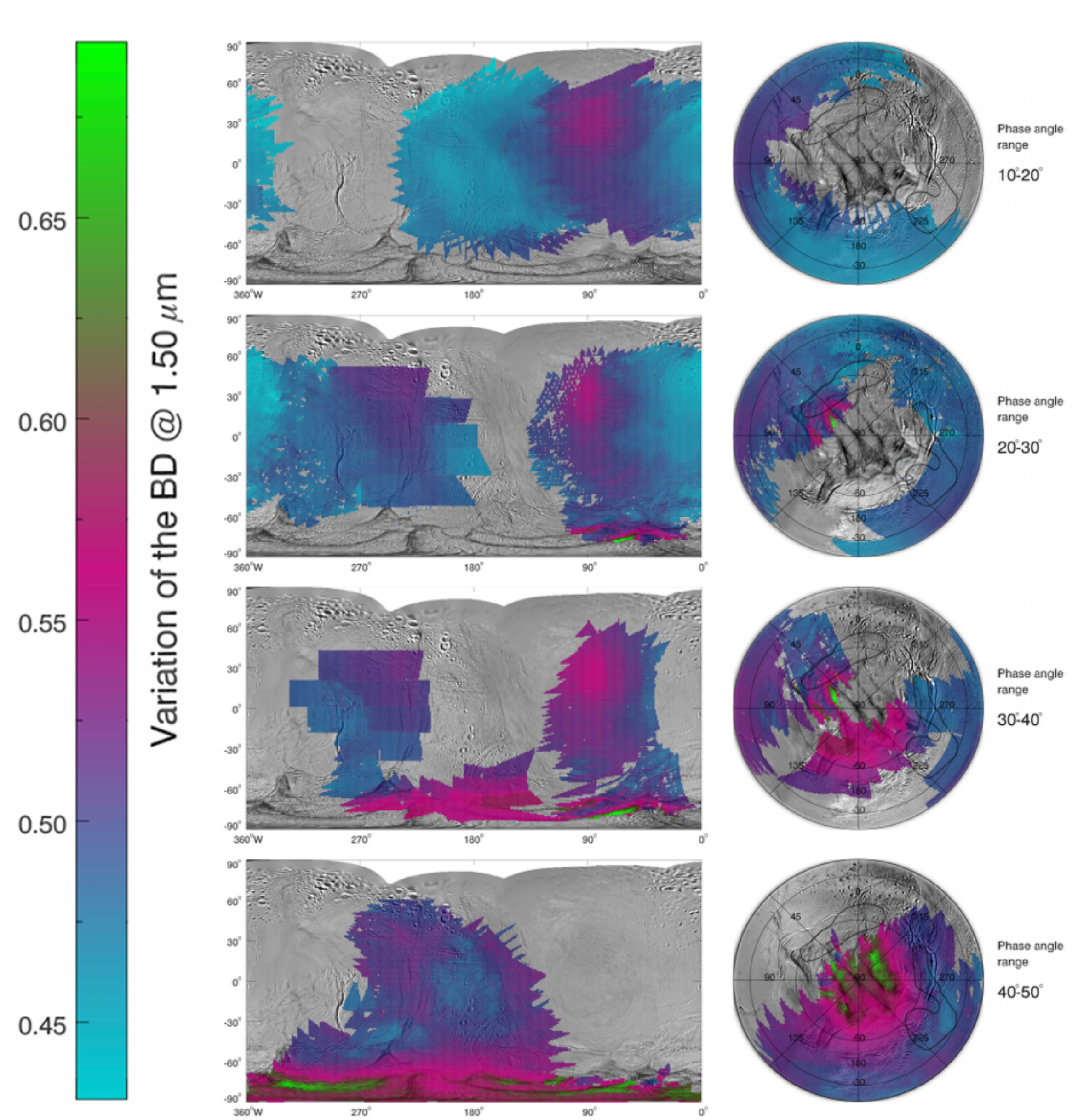
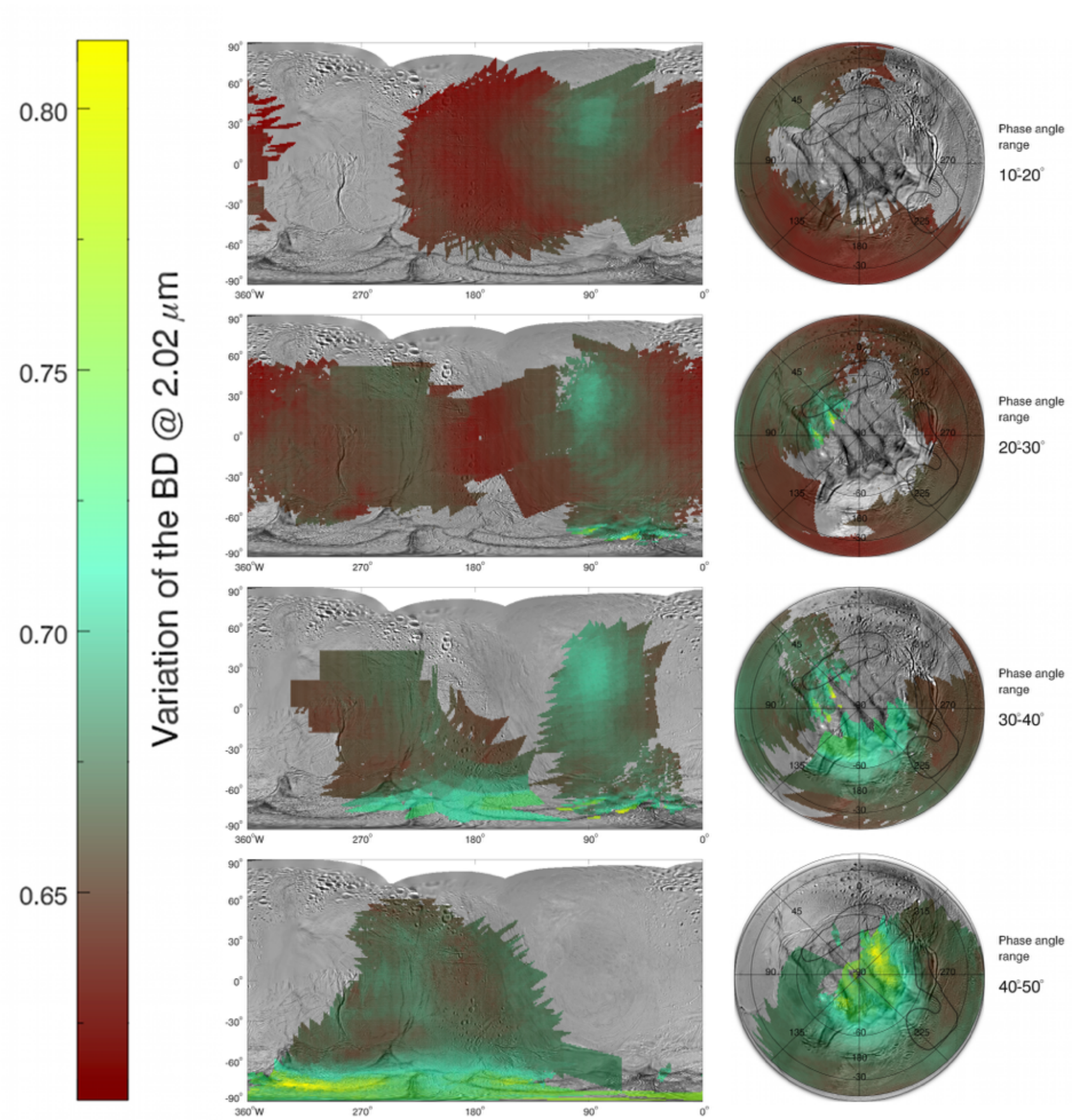


Figure 8



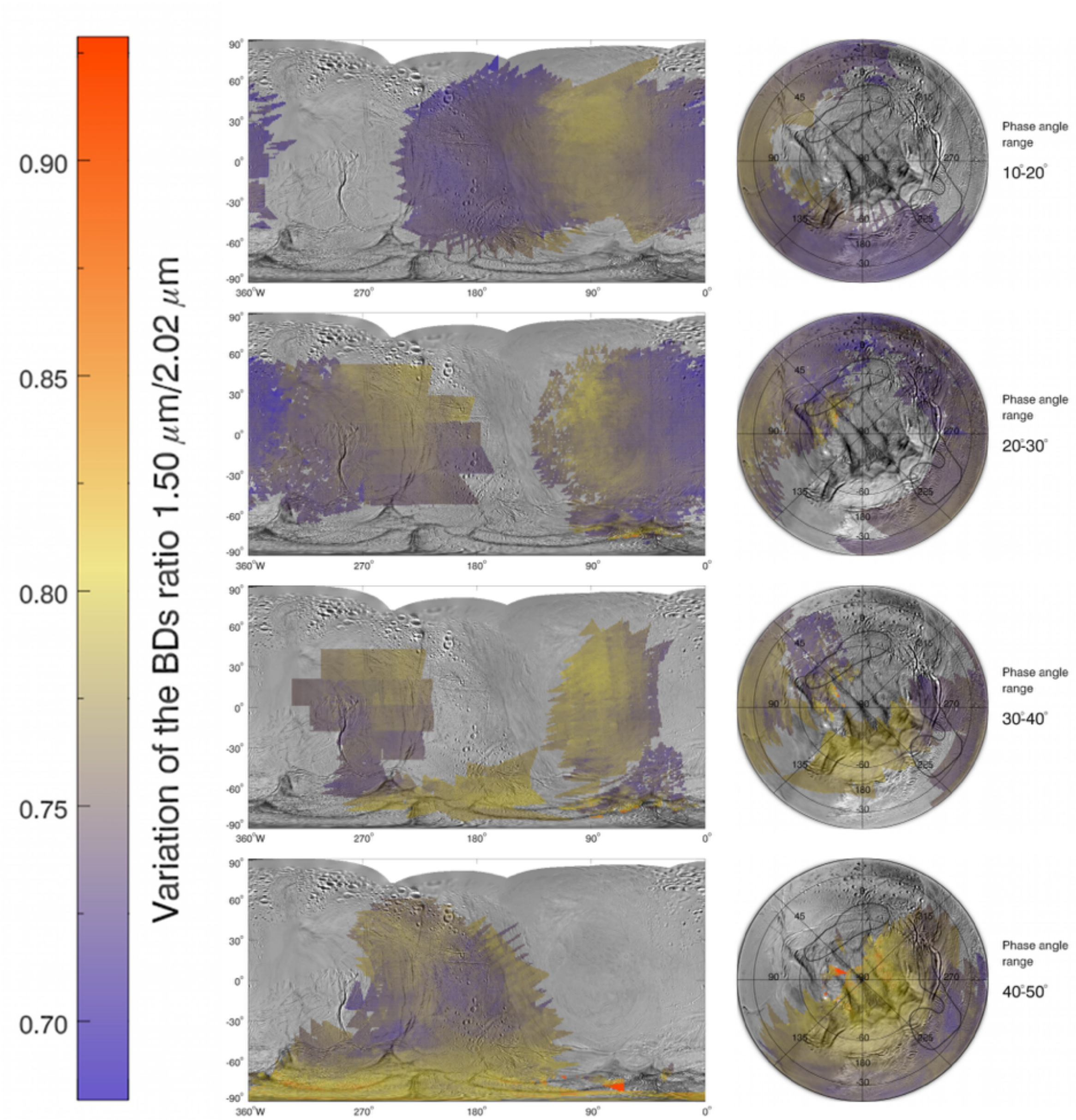
0.65
0.60
0.55
0.50
0.45
Variation of the BD @ 1.50 μm
360°W
270°
180°
90°
0°
Phase angle range
10°-20°
20°-30°
30°-40°
40°-50°

(a)

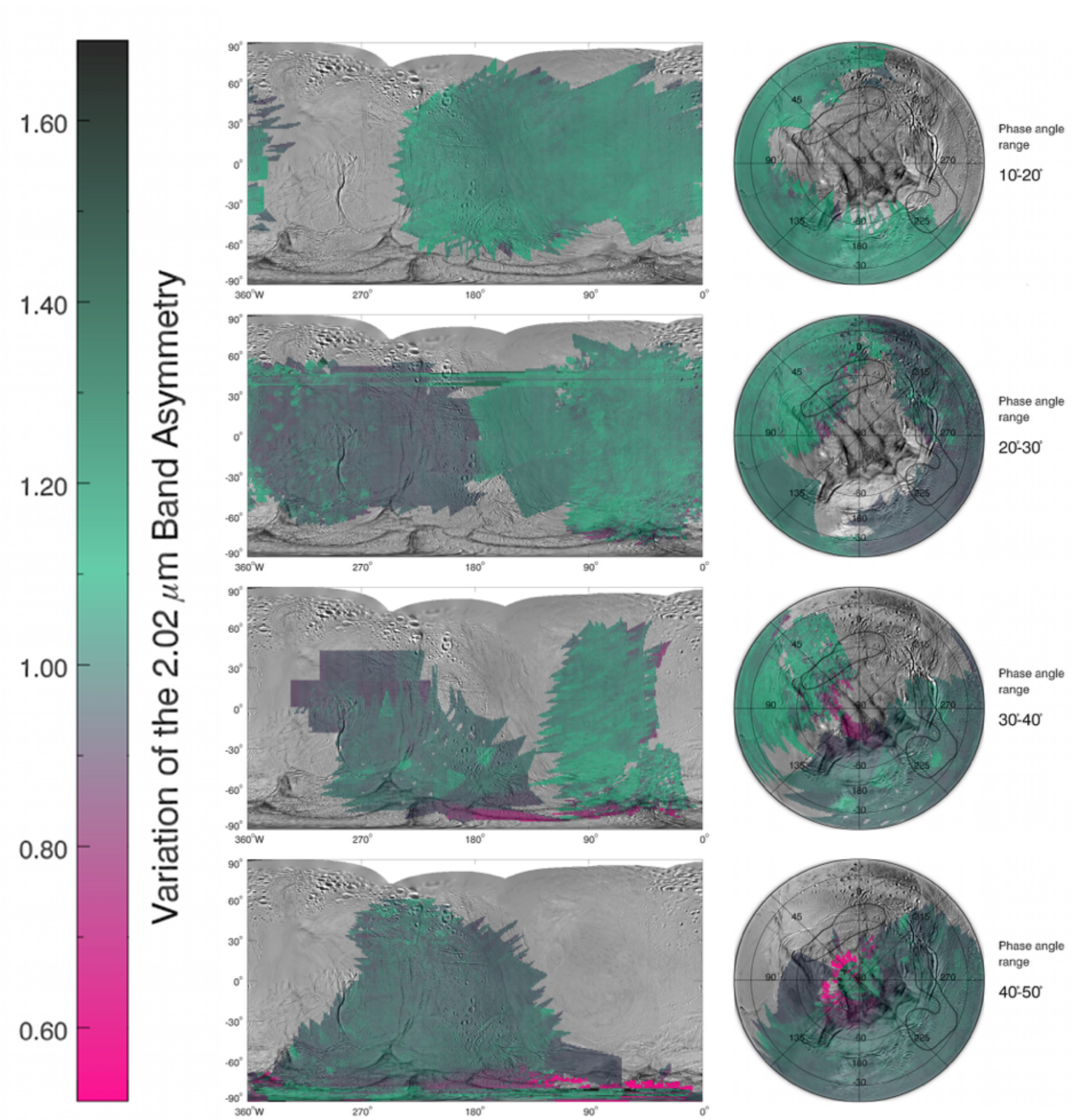


Variation of the BD @ 2.02 μm
0.80
0.75
0.70
0.65
Phase angle range
10-20°
Phase angle range
20-30°
Phase angle range
30-40°
Phase angle range
40-50°

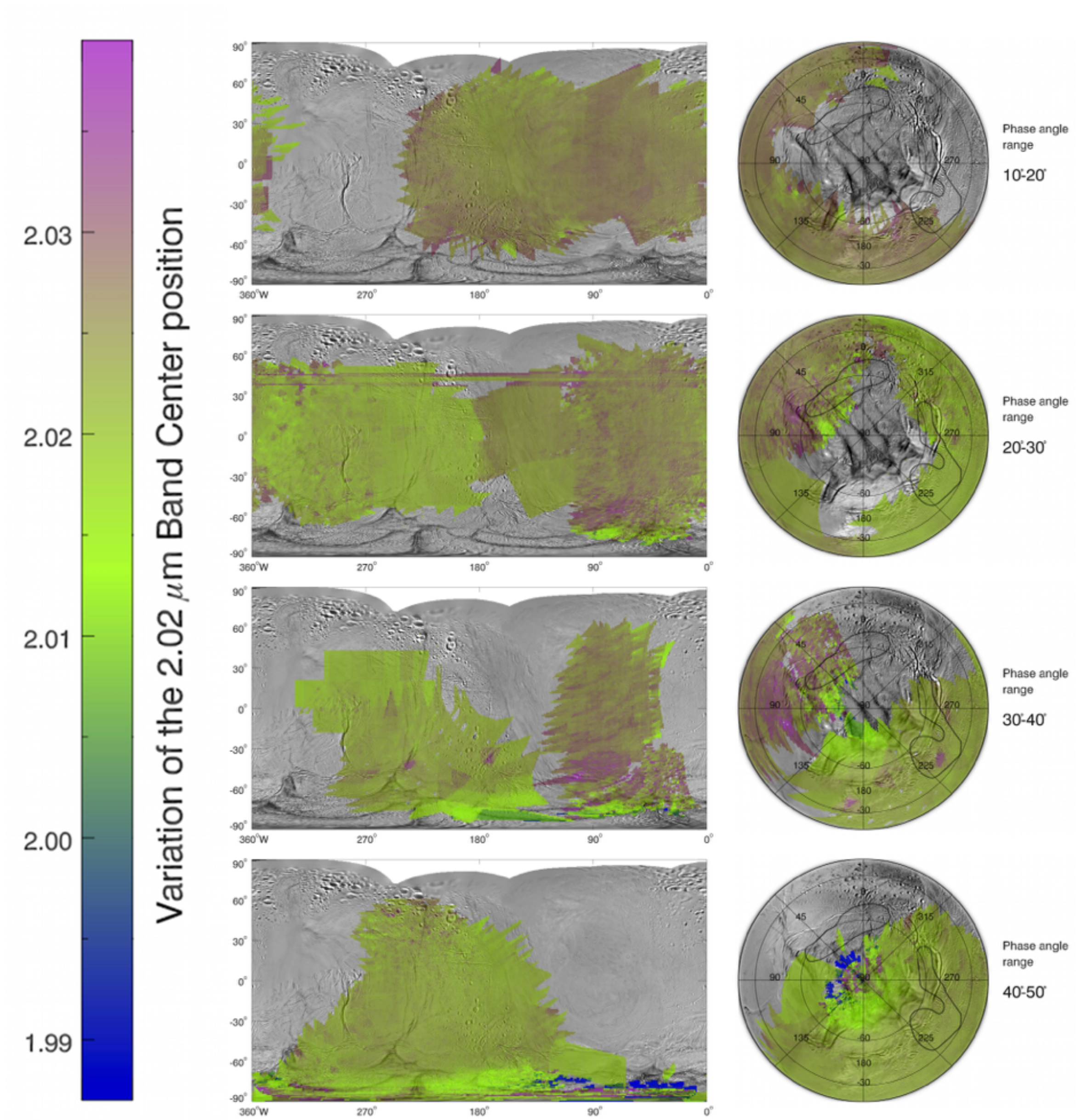
(b)


0.90
0.85
0.80
0.75
0.70
Variation of the BDs ratio 1.50 μm/2.02 μm
Phase angle range
10°-20°
Phase angle range
20°-30°
Phase angle range
30°-40°
Phase angle range
40°-50°

(c)


Variation of the 2.02 μm Band Asymmetry
1.60
1.40
1.20
1.00
0.80
0.60
Phase angle range
10°-20°
Phase angle range
20°-30°
Phase angle range
30°-40°
Phase angle range
40°-50°
360°W
270°
180°
90°
0°

(d)



2.03
2.02
2.01
2.00
1.99
Variation of the 2.02 μm Band Center position
Phase angle range
10°-20°
Phase angle range
20°-30°
Phase angle range
30°-40°
Phase angle range
40°-50°

(e)

Figure 9