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1 **Icy Saturnian Satellites: Disk-Integrated UV-IR Characteristics and Links to**
2 **Exogenic Processes**

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24 **Keywords.**

25 Saturn, satellites

26 Spectroscopy

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29

30

31 **Highlights.**

32 • Combined Cassini data result in hemispheric composite spectra of Saturn's moons.

33 • Ultraviolet and visible spectral trends are compared with exogenic processes.

34 • Results are consistent with E ring organics being responsible for coloring the moons.

35 • Electrons in the tens of keV range may be particularly effective at darkening and
36 reddening.

37

38

39 **Abstract.**

40 Combined Cassini observations obtained at similar observing geometries in the
41 ultraviolet through infrared spectral range, along with additional UV data from Hubble
42 Space Telescope where available, are used to study system-wide trends in spectral
43 albedos of the inner icy Saturnian satellites (Mimas, Enceladus, Tethys, Dione, Rhea).
44 We compare derived UV and visible geometric albedos, and UV absorption strengths, of
45 the leading and trailing hemispheres with E ring grain flux and charged particle
46 intensities (electrons and ions of varying energies) to those hemispheres. We find that the
47 UV absorption strength on the leading hemispheres is anti-correlated with E ring grain
48 flux. On the trailing hemispheres, the UV absorption strength is correlated with intensity
49 of electrons in the tens of keV range. We suggest that these relationships could imply
50 links with the organic component of the E ring. Radiolytic processing of organics causes
51 the products to become spectrally redder, increasing the UV absorption strength. Such
52 processing occurs while organic-rich grains are in the E ring, and increases with exposure
53 time in the E ring, such that grains interacting with Rhea are redder (more processed)
54 than those impacting Tethys. Further processing occurs on the trailing hemispheres of the
55 satellites, via radiolysis by electrons in the tens of keV range.

56

57 **1. Introduction.**

58 The inner moons of Saturn – Mimas, Enceladus, Tethys, Dione and Rhea - exhibit
59 remarkable **large spatial scale** albedo and color variations. The albedo trends with orbital
60 distance can be linked to a combination of processes including E-ring grain bombardment
61 and charged particle bombardment, as discussed by Schenk et al. (2011). One of the
62 fascinating concepts Cassini has learned about the Saturn system is that, though their
63 surface compositions are dominated by water ice, and evidently linked to E ring grain
64 bombardment (Buratti et al., 1990; Verbiscer et al., 2007), the icy satellites are spectrally
65 red: they are absorbing in the ultraviolet-visible wavelength region (wavelengths $< \sim 550$
66 nm) – a spectral characteristic not typical of water ice. This spectral behavior was
67 revealed initially, using HST data, for the leading and trailing hemispheres of Rhea and
68 Dione (Noll et al., 1997) and also shown in HST data for Enceladus and Tethys
69 (hemispheres not specified) (Noll, 2008). Cassini instruments have confirmed this
70 spectral behavior for all hemispheres of all of the inner medium sized moons of Saturn,
71 including Mimas. Thus, some basic questions are: What is the species or process that
72 causes this UV-visible spectral redness? Is the absorber a photolytic or radiolytic (i.e.
73 space weathered) product, or a combination of both? Is it native to the Saturn system?
74 What is the relationship (if any) to the Enceladus plume gases and E-ring? Here, we
75 utilize a system-wide study of UV-visible color trends to aid in understanding the source
76 of the absorber(s).

77 The oft-used approach to answering surface composition questions is to use visible
78 and near-infrared (VNIR) spectra, and indeed this has been done with success in the
79 Saturnian system (e.g., Clark *et al.*, 2008; Verbiscer *et al.*, 2006; Filacchione *et al.*, 2010).

80 However, VNIR spectra alone often do not tell the entire compositional story. The
81 reddish UV-visible absorption, present to varying degrees on all of the satellites, could be
82 due to several contributors, all of which are not very spectrally active in the near-IR, so
83 they cannot be uniquely identified by Cassini's Visible-Near Infrared Mapping
84 Spectrometer (VIMS) alone. In this study, we investigate the system-wide trends
85 affecting the surface compositions of Saturn's inner icy moons by creating composite
86 spectra at UV-IR wavelengths (100-5000 nm) using data from Cassini Ultraviolet
87 Imaging Spectrograph (UVIS), Imaging Science Subsystem (ISS) and Visual and
88 Infrared Mapping Spectrometer (VIMS).

89 Whereas Verbiscer et al. (2007) relate global visible geometric albedos of the moons
90 to the I/F of the E ring, here we look at visible and UV (300 nm) geometric albedos and
91 UV absorption depths of the leading and trailing hemispheres, to understand their
92 relationships to E ring flux, plasma flux and energetic electron intensity. Schenk et al.
93 (2011) describe possible effects of dust, plasma and energetic electrons on the visible
94 color; here we use composite spectra to quantify those effects, and focus on effects in the
95 UV (albedo and absorption).

96

97 **2. Background.**

98 *Previous Results.*

99 Icy satellite data from Cassini VIMS, ISS and UVIS have been analyzed
100 independently in the past, to produce useful results about the surface compositions and
101 interactions with the environments of these bodies. Here we describe some of the results
102 that have been obtained.

103 At visible wavelengths, a moderate negative (or blue) to neutral 350-550 nm slope
104 and high albedos are associated with fresh water icy surfaces. A moderate to positive (or
105 red) slope has been suggested to be the result of contamination induced by the presence
106 of very different materials, including complex organics produced by irradiation of simple
107 hydrocarbons (e.g. Moore et al., 1983; Moore and Hudson, 1998; Delitsky et al., 2017),
108 amorphous silicates (Poulet et al., 2003), carbonaceous particles (Cuzzi and Estrada,
109 1998), nanophase iron or hematite (Clark et al., 2008, 2012), tholins intimately mixed in
110 water ice grains (Ciarniello et al., 2011) or combinations of these materials.

111 Filacchione et al. (2010, 2012) performed a detailed studies of the entire suite of
112 VIMS disk-integrated observations of the icy satellites. For each satellite the disk-
113 integrated spectral slopes have been measured over two spectral ranges (350-550 and
114 550-950 nm). Some salient features arise in the groupings in the slope-slope plots over
115 these ranges. Mimas and Tethys have very flat slopes in the 550-950 nm range and
116 reddish slopes in the 350-550 nm range. Dione is also reddish in the 550-950 nm range
117 and distinctly bluer in the 550-950 nm range. Enceladus is also blue in the 550-950 nm
118 range and clearly also bluer than the other moons in the 350-550 nm range. Rhea is
119 redder than the other moons in both spectral ranges.

120 While the results of Filacchione et al. (2010, 2012) reveal the broad characteristics in
121 the 350-550 nm and 550-950 nm ranges and trace their radial distribution in the Saturnian
122 system (Filacchione et al., 2013), the results of Clark et al. (2008, 2012) and Stephan et al.
123 (2010, 2011) tell us about the finer-scale spectral features, mainly longward of 1000 nm.
124 The dominant VIMS-measured spectral features are due to H₂O ice. In addition to H₂O
125 ice, Clark et al. find evidence of trace amounts of CO₂, NH- and CH-bearing species and

126 H₂ on all the satellites. They also measure a variable blue peak, a local maximum in the
127 reflectance spectrum near 500 nm; shortward of this peak is the UV absorption. The blue
128 peak seems to be strongest in regions of intermediate abundances of dark material (e.g.,
129 at Dione) and at intermediate phase angles, but this needs to be studied further. Clark et al.
130 (2012) find that the best explanation for the blue peak, as well as the UV absorption, may
131 be sub-micron-sized H₂O ice in addition to nanograin hematite and nanograin iron; they
132 suggest that fine-grained metallic iron dust, e.g. in space-weathered meteorite dust,
133 contaminates the ice and that the competition of sub-micron ice, iron and hematite creates
134 the varying blue peaks and UV absorption observed throughout the system. **Rayleigh**
135 **scattering occurs when the size parameter $x (=2\pi D/\lambda) \ll 1$ (where **D** is the grain size**
136 **and λ is the wavelength); the blue peak is thought to be produced via Rayleigh**
137 **scattering by fine grains (e.g. Clark et al., 2008).**

138 The most significant analysis of ISS color data of Saturn's icy satellites so far has
139 been the work of Schenk et al. (2011), who constructed 3-color images using ISS
140 IR3/GRN/UV3 filters. They tracked color variations across the moons and linked large-
141 scale color patterns with exogenic processes. Some of the key results of Schenk *et al.*
142 include the mapping of blue-ish "lens" regions on the low latitude regions of the leading
143 hemispheres of Mimas and Tethys, the result of interactions with retrograde energetic (~1
144 MeV) electrons (Paranicas *et al.*, 2011). The relative blue-ness of the lens regions means
145 that they are relatively bright in the UV3 band range (centered at ~340 nm). The
146 interaction between the energetic electrons and the icy surfaces also results in regions of
147 relatively high thermal inertia (Howett et al., 2011). Spatial correlations are observed also

148 between equatorial lens regions and **daytime** temperatures inferred from reflectance
149 spectral behavior at 3600 nm (Filacchione et al., 2016).

150 Another key result of the Schenk et al. (2011) paper was the color map of Enceladus
151 plume fallout. The majority of the material from the plume is deposited on the surface in
152 the southern hemisphere with two wide fallout regions extending to the north between
153 180° and 270°W, and between 0° and 90°W (Kempf et al., 2010). This plume fallout
154 material is seen to be relatively blue-ish in the ISS images; **we suggest this is** due to an
155 increased abundance of fresh water ice. Notably, the regions not dominated by plume
156 fallout, which are likely dominated by E ring grains, are not bluish, they are yellow-ish.

157 The Cassini Ultraviolet Imaging Spectrograph (UVIS) covers the far-ultraviolet (far-
158 UV or FUV) spectral range, which includes a strong water ice absorption edge near 165
159 nm (Hendrix and Hansen, 2008). The water ice absorption edge dominates the UVIS
160 spectra of nearly every observed region on the icy satellites; however the slope of the
161 absorption edge can change, depending on the non-water ice species that are present, and
162 the magnitude and spectral shape of the spectrum longward and shortward of the 165 nm
163 edge can also vary depending on what other species are present.

164 Hendrix et al. (2010) pointed out, after careful photometric analyses of Enceladus
165 observations, that Enceladus has a lower-than-expected albedo in the 180-190 nm region.
166 (In fact, all of the icy moons are dark in the 180-190 nm range.) It was expected that
167 Enceladus' surface would be dominated by water ice, which has an albedo near unity in
168 this wavelength range; however, Enceladus' geometric albedo was closer to only ~0.3
169 (Hendrix et al., 2010). It was determined, by comparisons with broad-band data from
170 Hubble Space Telescope (HST), that to match Enceladus' spectral behavior a species that

171 absorbs rather steeply in the near-UV region (*i.e.*, between ~200 and 400 nm) must be
172 present. In that work, it was noted that NH₃ absorbs steeply in the near-UV, and is also
173 present in small amounts in the Enceladus plume (Waite *et al.*, 2009); a small amount of
174 NH₃ (<1%) is sufficient on the surface to replicate the absorption implied by the UVIS-
175 measured albedo. Hendrix *et al.* (2010) found that a species (more slowly absorbing than
176 NH₃) may also be present, such as a small amount of some type of tholin. More recent
177 HST data from the Cosmic Origins Spectrograph covering the 190-250 nm region are in
178 agreement with the UVIS data and the NH₃/tholin suggestion (Zastrow *et al.*, 2012).
179 Spectral modeling of VIS-IR Enceladus disk-integrated reflectance spectra by VIMS
180 indicates that an intraparticle mixture of 99.992% crystalline water ice and 0.008% Triton
181 tholin with grains of 63 μm is able to best fit the observations (Filacchione *et al.*, 2012).

182 Mimas is also very dark in the far-UV, but exhibits an interesting far-UV albedo
183 variation across the surface; the leading-southern region was measured (in February 2010,
184 a few months after equinox, when the sun began to move toward the north) to be darker
185 than other regions. The trailing hemisphere is the brightest region, likely due to
186 emplacement of relatively bright E-ring grains there. We have suggested (Hendrix *et al.*,
187 2012) that photolytically-produced hydrogen peroxide (H₂O₂) could be responsible for
188 the dark southern region. H₂O₂ is readily created in the uppermost layers of the icy
189 regolith that are sensed by UVIS, and absorbs strongly in the UV. The pathlengths sensed
190 by UVIS (**on the order of a few microns (Hendrix *et al.*, 2012)**) are generally not long
191 enough to detect the effects of the energetic electrons seen at longer wavelengths. At 340
192 nm (**where sensing depths are ~cm, (Hendrix *et al.*, 2012)**), the energetic electron “lens”
193 is sensed by ISS (Schenk *et al.*, 2011); the lens is relatively bright (blue) at 340 nm.

194 However, the production of H₂O₂ in the uppermost layers of the regolith may be enough
195 to largely mask the lens from UVIS. That being said, UVIS does likely sense a hint of the
196 lens in the “ansa” region – this is where the electron precipitation is more concentrated in
197 area (Hendrix et al., 2012) and where the lens is most prominent. The lens corresponds to
198 a thermal anomaly area where both CIRS (Howett et al., 2011) and VIMS (Filacchione et
199 al., 2016) have measured lower temperatures with respect to the nearby terrains. The best
200 fit to the disk-integrated Mimas reflectance measured by VIMS is achieved by means of
201 two populations of contaminants: 1) 0.1% tholin in intraparticle mixing with 97.9% water
202 ice grains and 2) 2% amorphous carbon in intimate mixing, with grain size of 58 μm
203 (Filacchione et al., 2012).

204

205 *Processes.*

206 In this study, we consider disk-integrated spectra of the moons, which we expect
207 are controlled more by exogenic processes than by endogenic/geologic processes that
208 would be expected to operate on smaller, more localized scales. Furthermore, in
209 considering the UV-visible spectral shape and albedos, we are mindful that these are
210 characteristics of the uppermost surface layer, so consider that they are related closely to
211 exogenic effects.

212 Bombardment by plasma and energetic electrons. Corotating cold plasma will tend to
213 impact the trailing hemispheres of the icy moons (centered on 270°W), often resulting in
214 a darkening of the surfaces in a target shape related to the cosine of the angle to the
215 plasma ram direction. Radiolysis by electrons and ions has important chemical effects as
216 well, producing species such as H₂O₂, O₂ and O₃ in the water ice-rich regoliths (e.g.

217 Johnson et al., 2008). **Most electrons preferentially hit the trailing hemisphere but**
218 **those greater than about 0.5 to 1.5 MeV preferentially hit the leading (Paranicas et**
219 **al., 2011; Nordheim et al., 2017); this interaction results** in an increase in thermal
220 inertia (Howett et al., 2011) and creating the blue lens-shaped feature (Schenk *et al.*,
221 2011).

222 E-ring grain coating/bombardment. Hamilton and Burns (1994) showed that E-ring
223 grains will tend to impact primarily the trailing hemisphere of Mimas and the leading
224 hemispheres of the satellites that orbit outside Enceladus' orbit (Tethys, Dione, Rhea).
225 Juhasz and Horanyi (2015) provide updated models of the dust interactions, wherein the
226 bombardment on Tethys **and Rhea is focused more toward the** sub- and anti-Saturnian
227 parts of the leading hemisphere **rather than toward the apex of the leading**
228 **hemisphere.** E-ring grain bombardment has been suggested to have a brightening effect
229 on the satellites, affecting the overall visible-wavelength brightness of all the inner
230 moons (Verbiscer *et al.*, 2007) due to coating of the surface with fresh material and/or
231 sandblasting of the grains (**Hamilton and Burns, 1994**). We note that, despite these
232 effects of E-ring grain bombardment, however, *the surfaces of the satellites are UV dark*
233 (as seen by UVIS, discussed above) – implying that if E-ring grains dominate the optical
234 properties of the surfaces, then we are sensing in the UV-visible a non-ice component of
235 the E-ring (because H₂O ice is bright in the UV). Or those non-ice components could be
236 darkened/alterd by weathering that occurs on the same timescale as E ring grain
237 bombardment (e.g., Hand and Carlson 2015 and references therein). Cassini's Cosmic
238 Dust Analyzer (CDA) indicates that E ring grains are made up of two primary types of
239 grains. Type-1 grains are pure water ice particles (Postberg et al., 2008). Type-2 grains,

240 comprising ~25% of E-ring grains, are dominated by organic species (Postberg *et al.*,
241 2008, 2017). Salts are observed by CDA in the plume grains but are depleted in the
242 population of grains escaping to the E ring (Postberg *et al.*, 2009). Silicate dust streams
243 have also been observed using CDA (Hsu *et al.*, 2011).

244 Photolysis. Photolysis is a very efficient process for breaking up water ice (in the
245 uppermost few microns of the regoliths) and producing species such as H₂O₂. Photolysis
246 could play a role in the production of O₃ at Rhea and Dione (Noll *et al.*, 1997), and is key
247 in the production of Saturn's rings' O₂ atmosphere (Johnson *et al.*, 2006). As mentioned,
248 Hendrix *et al.* (2012) suggest that photolytically-produced H₂O₂ is present in the topmost
249 layer of Mimas' regolith, as detected by UVIS.

250 Bombardment by exogenic dark material. **Clark *et al.* (2008, 2012) suggested, based**
251 **on high resolution imaging and spectroscopy, that there is an exogenic source of**
252 **dark material, onto the trailing hemispheres of Dione (Clark *et al.*, 2008; Stephan *et***
253 **al., 2010) and Rhea (Stephan *et al.*, 2012), where it is observed that the older**
254 **terrains have higher concentrations of dark materials.** The exogenic source is unclear;
255 the Phoebe ring (Verbiscer *et al.*, 2009) is a possible source, though its retrograde-
256 orbiting grains would impact mainly the leading hemisphere of Dione, and are considered
257 of very low flux inside of Titan's orbit (Tamayo *et al.*, 2011). Another source is
258 meteoritic dust which Cuzzi *et al.* (2009 and references therein) have argued is a source
259 of contamination of the main rings. The dark material (Stephan *et al.*, 2010; 2012) could
260 be linked to an exogenic process such as magnetospheric processing and on smaller
261 scales the dark material is interrupted by craters and/or geologic terrains (e.g. graben).

262

263 **3. Instruments and Datasets.**

264 To investigate the problem of the UV-visible absorber in the Saturnian system, we
265 create composite disk-integrated spectra of of Mimas, Enceladus, Tethys, Dione and
266 Rhea, using data from Cassini VIMS, ISS and UVIS. **Because many of the exogenic**
267 **processes discussed in Sec. 2 may result in leading-trailing hemispheric differences,**
268 **we analyzed disk-integrated spectra of both the leading and trailing hemispheres of**
269 **Tethys, Dione and Rhea. In the case of Mimas, disk-integrated observations are**
270 **limited and we were unable to find satisfactory observations of both the leading and**
271 **trailing hemispheres. For Enceladus, because previous observations had indicated**
272 **that leading-trailing asymmetries are largely insignificant, we opted to include just a**
273 **single observation in our analysis.**

274 The VIMS instrument (Brown et al., 2004) covers the 0.35-5.1 μm spectral range by
275 imaging a 1.8° FOV with 64 pixels. The experiment consists of two imaging
276 spectrometers (VIS and IR) observing the same field of view in two spectral ranges.
277 VIMS-V is the Italian-made imaging spectrometer covering the 0.35–1.05 μm range in
278 96 spectral channels and spatial resolutions of 500 x 500 (nominal) or 166 x 166 (high
279 resolution) $\mu\text{rad}/\text{pixel}$ (Miller *et al.*, 1996). VIMS-IR is the US-made channel covering
280 the 0.8-5.1 μm spectral range with 256 spectral channels and spatial resolutions of 500
281 (nominal) or 500 x 250 (high resolution) $\mu\text{rad}/\text{pixel}$.

282 The Cassini imaging science sub-system (ISS) consists of two cameras, the narrow
283 angle camera (NAC) and the wide angle camera (WAC) (Porco et al., 2004). Both
284 cameras use a 1024 x 1024-element charge-coupled device (CCD) array detector. Image
285 scale is 5.9907 $\mu\text{rad}/\text{pixel}$ for the NAC and 59.749 $\mu\text{rad}/\text{pixel}$ for the WAC. In-flight

286 calibration of the cameras is described by West et al. (2010). Each camera contains two
287 filter wheels; the filter coverage for the NAC is shown in Porco et al. (2004). For the
288 purposes of this study, we have focused on observations where ISS has used one or more
289 of its UV filters, UV1 (258 nm), UV2 (298 nm) or UV3 (338 nm), to extend spectral
290 coverage as close to UVIS as possible.

291 The UVIS (Esposito et al., 2004) far-UV channel covers the \sim 100-194 nm region.
292 UVIS provides simultaneous spectral and one-dimensional spatial images. The detector
293 format is 1024 spectral pixels by 64 spatial pixels. Each spatial pixel subtends an angle of
294 1 mrad projected on the sky. The low-resolution slit has a spectral resolution of 0.48 nm
295 and subtends an angle of 1.5 mrad. The high-resolution slit has a spectral resolution of
296 0.275 nm and subtends an angle of 0.75 mrad; this slit is usually used for close-up
297 satellite encounters. The second spatial dimension is acquired by slewing the UVIS slit
298 across the target body.

299 Due to the synergistic nature of the Cassini spacecraft and the Icy Satellites Planning
300 Group, during most icy satellites observations, all remote sensing instruments participate,
301 so that simultaneous ISS, UVIS and VIMS data are acquired. UVIS, ISS and VIMS are
302 all boresighted, so simultaneous **disk-integrated** observations of the same target are
303 straightforward. To create disk-integrated composite spectra of the icy satellites, we use
304 simultaneous observations where possible. This eliminates the need to photometrically
305 correct one dataset to match another. This is challenging however, due to resolution
306 issues: the distant observations that are most useful for UVIS (when the target body is
307 <1.5 mrad across, it fits entirely within the UVIS slit) tend to be too low in resolution for
308 VIMS. So we have in several cases found it useful to use non-simultaneous observations

309 of similar geometry (i.e. similar phase angle and sub-spacecraft longitude). **For non-**
310 **simultaneous observations, we have used observations at as-similar-as-possible**
311 **phase angles; we estimate (based on phase curves from Royer and Hendrix (2014)**
312 **that the phase angle differences are small enough (e.g. between ISS and UVIS) that**
313 **we are not introducing a significant spectral shift in our composite spectra.** Using
314 observations of identical viewing geometry, we have confirmed good agreement between
315 ISS and VIMS at overlapping wavelengths, so we can overplot non-simultaneous VIMS
316 data (of the appropriate hemisphere) for some observations by scaling to ISS. VIMS and
317 ISS data have a region of spectral overlap; there is a small gap between UVIS and ISS
318 (194~260 nm) but we nevertheless obtain a strong sense of the shape of the spectrum in
319 the region. In this report, we use HST Space Telescope Imaging Spectrometer (STIS) and
320 Faint Object Spectrograph (FOS) data to fill in the spectral gap between ISS and UVIS,
321 where HST data are available. Knowing the ISS-measured whole-disk albedo for a
322 particular observational geometry, we can simply overplot the existing HST data using
323 the overlap in wavelength coverage, increasing the spectral coverage.

324

325 **4. Results: Composite Spectra**

326 Disk-integrated spectra of the icy moons, using combined data from Cassini and from
327 HST instruments, are shown in Fig. 1. Information on the observations that were used for
328 these composite spectra is shown in Table 1. These composite spectra (Fig. 1) highlight
329 regional compositional variations within the inner Saturnian system. The spectra of all
330 these satellites are bright and spectrally relatively flat at visible wavelengths longer than
331 ~500 nm; the water ice absorption features near 1.5, 2.0 and 3.0 μm dominate the infrared

332 spectrum. Shortward of 500 nm the surfaces become absorbing with decreasing
333 wavelength, resulting in reddish spectra. The satellites exhibit flattish-to-bowl-shaped
334 spectra in the ~200-350 nm range and demonstrate the 165 nm water ice absorption edge,
335 in varying strengths. The HST spectra demonstrate the broad band at 260 nm discussed
336 by Noll et al. (1997) (here we do not focus on the cause of the absorption and rather focus
337 on the UV dropoff). On Dione and Rhea, the composite spectra may require a dramatic
338 decrease in reflectance near 200 nm, in order to meet up with the UVIS data (but the
339 HST/FOS data for Dione and Rhea do not have the spectral extent of the STIS data
340 shown for Enceladus and Tethys).

341 In Fig. 2, we show normalized spectra of the leading and trailing hemispheres of
342 Tethys, Dione and Rhea to directly compare these regions. These plots show that the UV-
343 visible absorber is stronger on the trailing hemisphere of Tethys and Dione than on those
344 leading hemispheres, and that the leading-trailing spectral dichotomy is strongest on
345 Tethys and minimal on Rhea. The differences in water ice absorption band depths in the
346 IR (near 1.5 and 2 microns) have largely been attributed to grain size differences (e.g.
347 Stephan *et al.* 2010; Scipioni et al., 2013, 2014). The comparison between the disk-
348 integrated UV-visible (100-900 nm) spectrum of Rhea's leading and trailing hemispheres
349 shows no significant spectral differences. However, since we know that Rhea's LH is
350 brighter than its trailing hemisphere (e.g. Verbiscer et al., 2007; see also Table 2), this
351 suggests that (a component of) Rhea's trailing hemisphere darkening agent is spectrally
352 bland throughout the ~150-900 nm region. The IR water ice absorption depths on Rhea's
353 leading and trailing hemispheres are similar in depth, consistent with overall similar
354 water ice grain sizes and abundances.

355 Figure 3 displays all normalized reflectance spectra together. The UV absorption edge
356 that begins at ~ 500 nm is strongest for Rhea, the trailing hemispheres of Dione and
357 Tethys, and possibly Mimas; it is least strong for Enceladus and the leading hemispheres
358 of Dione and Tethys. This UV absorption edge strength translates to lower albedos in the
359 far- and near-UV for Rhea and the trailing hemispheres of Dione and Tethys, and higher
360 far- and near-UV albedos for Mimas and the leading hemispheres of Dione and Tethys;
361 Enceladus exhibits the highest far- and near-UV albedo. This suggests that the absorbing
362 species is/are present in greater abundances on the trailing hemispheres of Dione and
363 Tethys and on Rhea. Absolute reflectance spectra are presented in Fig. 4, where we have
364 scaled by the visible albedos as listed in Table 2.

365

366 **5. Relationships with Exogenic Processes**

367 The composite spectra in Figs. 1-4 can be used to study the inner system surface
368 compositions of the satellites to understand large-scale exogenic effects. In Figs. 5 and 6
369 we compare the visible and UV geometric albedos and UV absorption depths (UV/visible
370 ratio) with E ring grain fluxes and electron fluxes to look for trends. In these figures, we
371 have used the 300 nm albedos from Fig. 4 as the UV albedo and to represent the UV
372 absorption, we use the ratio of the 300 nm albedo to the ~ 600 nm albedo from Fig. 4.

373 In Figure 5, E ring fluxes to the leading and trailing hemispheres have been estimated
374 based on the relative fluxes from Juhasz and Horanyi (2015) and Kempf et al. (2017,
375 their Fig. 11) (M. Horanyi, *pers. comm.*). The albedos of the leading hemispheres
376 decrease with E ring grain flux (Fig. 5a). On the trailing hemispheres (Fig. 5b), Mimas's
377 albedo is lower than expected if only related to E ring grain flux. (Verbiscer et al. (2007)

378 tied the overall (not leading or trailing hemisphere) visible albedo with E ring albedo, not
379 flux). The UV absorption (Figs. 5c and 5d) increases in strength with decreasing E ring
380 grain flux. The absorption is generally stronger on each trailing hemisphere, than on the
381 leading hemispheres.

382 In Fig. 6, we compare albedo and UV absorption with intensity of tens of keV
383 electrons (using data from Paranicas et al., 2011). These electrons are expected to
384 primarily bombard the trailing hemispheres of the satellites (e.g. Patterson et al., 2012).
385 We find that the trailing hemisphere UV and visible albedos roughly decrease as electron
386 intensity increases (Fig. 6a). The UV absorption on the trailing hemisphere (Fig. 6b)
387 roughly increases with 35 keV electron intensity. The trailing hemisphere UV absorption
388 is similar for Tethys, Dione and Rhea, which may suggest some level of saturation. We
389 have also compared our leading and trailing hemisphere albedos and UV absorptions with
390 intensities of hundreds of keV to MeV electrons (Paranicas et al., 2011; Kollmann et al.,
391 2011), and with plasma electrons and ions (Persoon et al., 2006, 2009); we find that the E
392 ring grain and ~tens of keV electrons are the only species that appear to demonstrate
393 relationships with our leading hemisphere (E ring grain) and trailing hemisphere (tens of
394 keV electron) data. MeV particles could also cause the same absorbing effect but they are
395 so few in number that it is harder to see a correlation.

396 In Fig. 6, the trailing hemisphere UV and visible albedos roughly decrease as electron
397 intensity (tens of keV) increases. The UV absorption on the trailing hemisphere increases
398 with 35 keV electron intensity; the UV absorption is similar for Tethys, Dione and Rhea,
399 suggesting some level of saturation. These plots use 35 keV electron intensity (Paranicas

400 et al., 2011) as a proxy for ~tens of keV electrons, which primarily impact the trailing
401 hemispheres.

402

403 **6. Discussion and Implications**

404 The relationships between observed UV absorption strength on the satellites and E
405 ring grain flux and electron intensity (Figs. 5 and 6) demonstrate correlations that, while
406 not implying causation, lead to potential implications for system-wide processing. We
407 suggest that the non-ice component of the E ring grains, namely the organic species,
408 plays an important role in coloring the surface of the satellites. Postberg et al. (2008,
409 2017) show that ~25% of E ring grains include an organic component. The evolution of
410 frozen hydrocarbons (e.g. CH₄) in the laboratory has been discussed (e.g. Strazzulla et al.,
411 1983a, 1983b; deVries et al., 1984; Foti et al., 1984; Strazzulla, 1986; Lanzerotti et al.,
412 1987; Compagnini et al., 2009); after dosing with protons, the hydrocarbons are
413 converted to a yellow organic residue. Upon further irradiation, the yellow organic
414 residue becomes brown and then black as carbonization occurs. We suggest that a similar
415 processing of grains occurs within the E ring, and that further processing occurs after the
416 E ring grains have impacted the surfaces of the satellites. Postberg et al. (2008) point out
417 that E ring grains have experienced plasma sputtering for several decades whilst reaching
418 the outer E ring near Rhea. **The timescales involved in the chemical processing**
419 **resulting in reddening are unclear; Brunetto et al. (2006) provide estimates for**
420 **reddening (in the 0.68-1.25 μm range, so longward of what we consider here) for 10**
421 **eV/16 amu, 50 eV/16 amu and 100 eV/16 amu cases. All cases provide significant**
422 **reddening (2-26%/1000 Å), though similar studies for the spectral region we**

423 **consider here were not found in a literature search. However, based on these results,**
424 **it is reasonable to assume that** the E ring grains that make it to Rhea are likely to be
425 redder and darker than the “fresher” ones that impact Tethys. Radiolysis by ~10 keV
426 electrons on the trailing hemispheres of the moons then further darken and redden the
427 material there. The region of higher E ring grain fluxes (close to Enceladus) is where E
428 ring grains are fresher and less processed due to lower electron (tens of keV) irradiation.
429 We see that satellites with lower E ring fluxes, and higher electron intensity (e.g. Rhea)
430 have strong UV absorption and lower albedos than satellites (e.g. Enceladus) with high E
431 ring grain fluxes and lower electron intensity. Our results show that electrons in the ~tens
432 of keV energy range may be particularly effective at reddening; this is consistent with
433 results (Hand and Carlson, 2015) in the Jovian system.

434 There is evidence in the Saturnian system for low-level carbonization occurring. In
435 Fig. 2, comparison between the disk-integrated UV-visible (100-900 nm) spectrum of
436 Rhea’s leading and trailing hemispheres shows no significant spectral differences.
437 However, since we know that Rhea’s leading hemisphere is brighter than its trailing
438 hemisphere (e.g. Verbiscer et al., 2007; see also Table 2), this suggests that (a component
439 of) Rhea’s trailing hemisphere darkening agent is spectrally bland throughout the ~150-
440 900 nm region. This spectrally bland, low-albedo component could be E ring organics
441 that have been carbonized due to higher levels of processing (i.e. greater levels of
442 exposure).

443 These results of UV absorption strength in the Saturn system are consistent with those
444 of Filacchione et al. (2013), who used *Cassini* VIMS data to show that the spectral slope
445 (0.35-0.55 μm) increases (becomes redder) with distance from Enceladus. Filacchione et

446 al. (2013) noted that because Enceladus is the primary source of the E ring, that the E
447 ring grains likely play a role in influencing the spectral properties of the moons. Here we
448 present a related hypothesis, that the source of reddening is the organic component of the
449 E ring. We note that Clark et al. (2008, 2012) have shown that models including nano-
450 iron/nano-hematite can be used to fit VIMS spectra of Phoebe, Iapetus, Hyperion and
451 Dione, including the UV absorption and other spectral details. Here we suggest an
452 alternative model that is consistent with the composition of the E ring (~25% organics),
453 lab work on radiolysis of organic species, and observed large-scale trends in the inner
454 Saturnian system.

455

456 **7. Conclusions.**

457 We have compiled composite spectra of the Saturnian satellites using a combination
458 of Cassini UVIS, ISS and VIMS data, along with HST data. We have used these
459 composite spectra to investigate large-scale trends in the system relating to albedo and
460 UV absorption (i.e. reddening).

461 Our results show that both albedo and UV absorption are correlated with E ring grain
462 flux and electron intensity. On the leading hemispheres, the albedo increases with E ring
463 grain flux. On both the leading and trailing hemispheres, the UV absorption decreases in
464 strength with increasing E ring grain flux. On the trailing hemispheres, where electron
465 bombardment (in the tens of keV range) occurs, the albedo decreases, and the UV
466 absorption strength increases, with electron intensity. The UV absorption is also stronger
467 on the trailing hemispheres than on the leading hemispheres. We suggest that these trends
468 are related to the organic component of the E ring (~30% of the E ring grains). These

469 organics are expected to darken and redden with exposure, such that the grains impacting
470 Rhea are likely to be darker and redder (though fewer in number) than those that impact
471 Enceladus. In addition, the UV absorption, stronger on the trailing hemispheres than on
472 the leading hemispheres, is increased there due to continued radiolysis of the organics on
473 the surfaces of the moons. At Rhea, and likely at Dione as well, we suggest that some of
474 the dark component could be due to carbonization as a result of relatively high levels of
475 processing of those grains, both within the E ring and on the surfaces. Future studies of
476 the composite spectra, and spectral modeling of the UV-5 micron signatures, may help to
477 elucidate the exact nature of organic species.

478

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484

485

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643 **Table 1. Observation Geometry**

Satellite		date	altitude	phase angle	sub-Cassini longitude
Mimas	UVIS	2005-265	778,733 km	43°	237°W
	ISS	2006-324	153,472 km	43°	223°W
	VIMS	2005-214	62,949 km	53°	232°W
Enceladus	UVIS	2008-178	1,283,650 km	15°	76°W
	ISS	2008-178	1,283,650 km	15°	76°W
	VIMS	2010-355	37,546 km	15°	163°W
Tethys	UVIS	2008-235	1,342,906 km	10°	59°W
	ISS	2008-235	1,342,906 km	10°	59°W
	VIMS	2008-294	1,154,802 km	8.6°	89°W
	UVIS	2005-264	1,377,469 km	59°	239°W
	ISS	2006-056	~145,000 km	63°	252°W
	VIMS	2004-302	3,948,311 km	65°	254°W
Dione	UVIS	2005-264	1,341,140 km	34°	95°W
	ISS	2011-275	203,530 km	26°	110°W
	VIMS	2005-284	~280,000 km	22°	120°W
	UVIS	2005-066	1,588,567 km	46°	311°W
	ISS	2005-214	242,838 km	44°	274°W
	VIMS	2005-213	~268,000 km	41°	257°W
Rhea	UVIS	2006-054	933,841 km	26°	92°W
	ISS	2006-055	356,446	27°	107°W
	VIMS	2008-232	429,608 km	27°	6°W
	UVIS	2007-303	2,704,651 km	13°	310°W
	ISS	2006-017	243,916 km	30°	312°W
	VIMS	2006-017	226,162 km	35°	309°W

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652 **Table 2.**

Satellite	R _S		E ring grain flux ⁺ (g/m ² /s)	Electron intensity (35 keV)** (electrons cm ⁻² s ⁻¹ sr ⁻¹ keV ⁻¹)	Visible albedo*	UV albedo (300 nm) ⁺⁺
Mimas	3.08	leading	4.3e-14		0.919	0.583
		trailing	4.3e-12	400.000	1.007	0.639
Enceladus	3.95	leading	3.08e-12		1.328	0.881
		trailing	2.64e-12	260.000	1.424	0.944
Tethys	4.89	leading	1.28e-12		1.287	0.868
		trailing	1.6e-13	1800.00	1.174	0.652
Dione	6.26	leading	9.5e-14		1.233	0.799
		trailing	9.5e-15	4000.00	0.808	0.424
Rhea	8.75	leading	7.2e-16		1.07	0.572
		trailing	8.4e-16	19000.0	0.842	0.439

653 *from Verbiscer et al. (2007)

654 **from Paranicas et al. (2011)

655 + estimates to leading and trailing hemispheres from Juhasz and Horanyi (2015)

656 ++300 nm albedos from Fig. 4

657 R_S – Saturn radii

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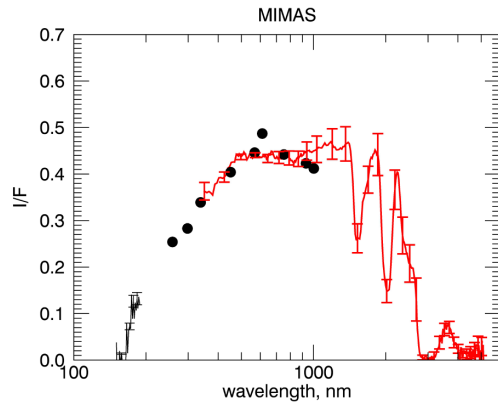
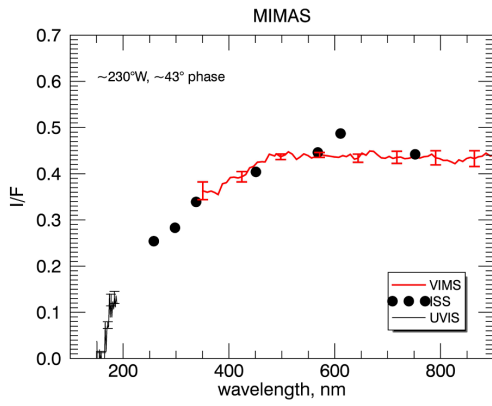
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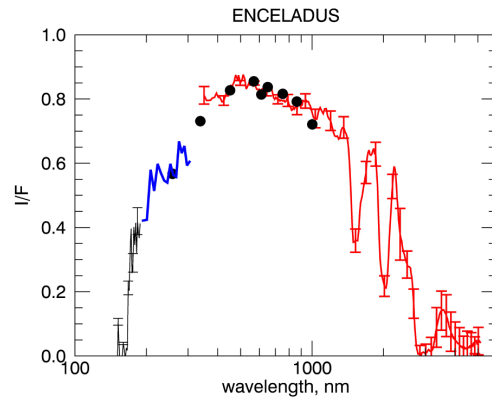
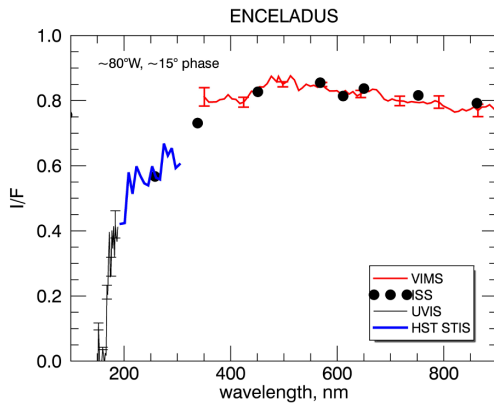
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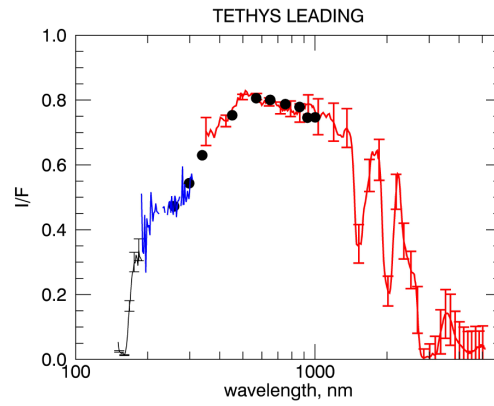
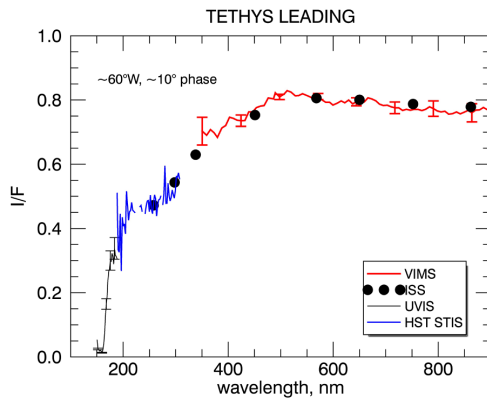
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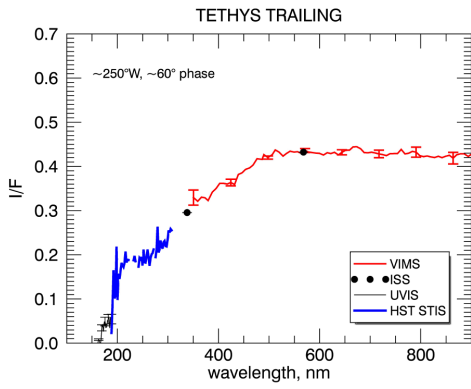
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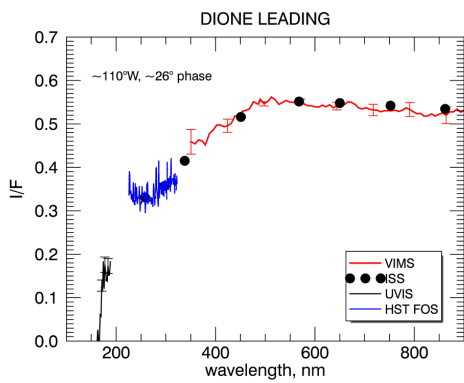
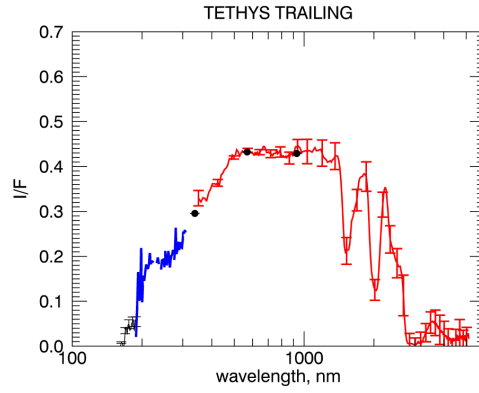
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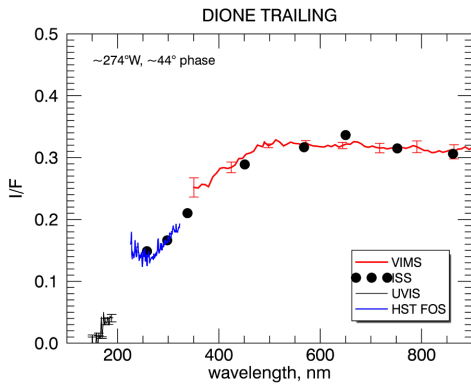
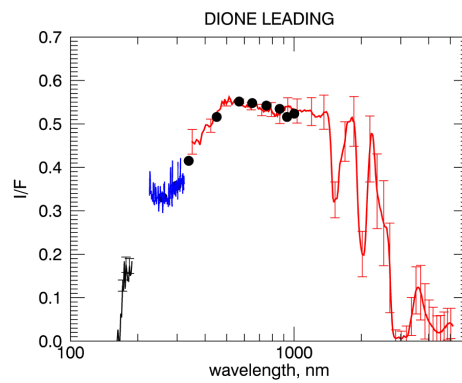
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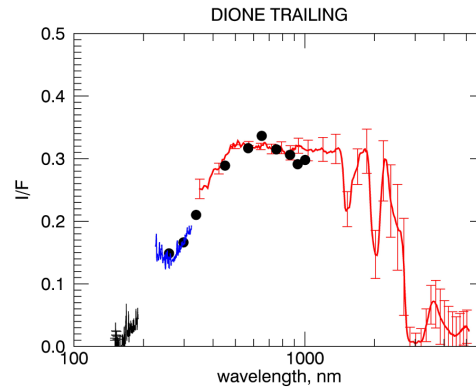
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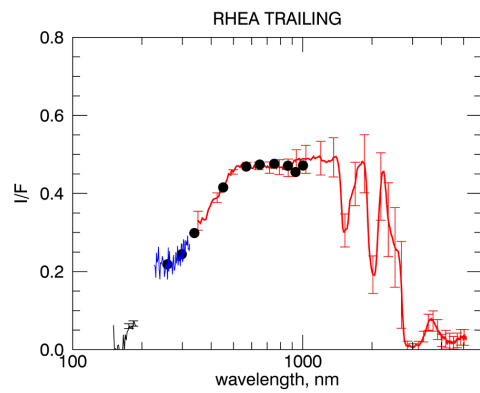
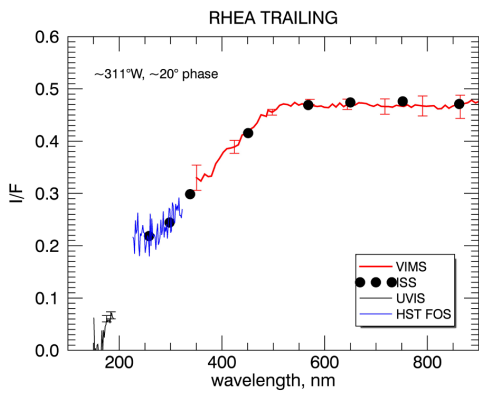
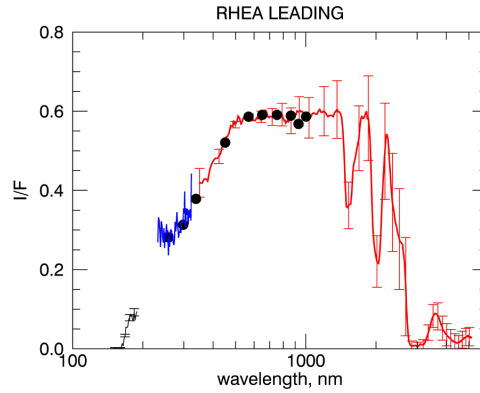
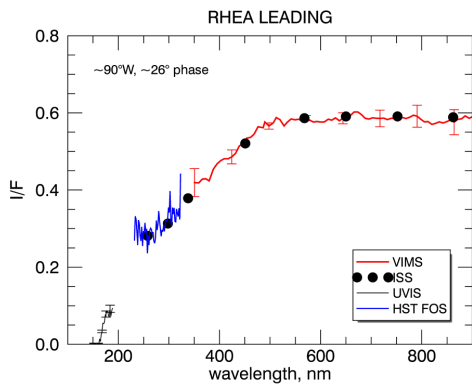


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672 **Figure 1.** Composite spectra of Mimas, Enceladus, Tethys, Dione and Rhea using data
 673 from Cassini UVIS, ISS and VIMS, and HST STIS/FOS. Observational geometry for
 674 each observation is indicated in Table 1. Representative error bars for UVIS and VIMS
 675 data are shown; the error bars on the ISS data are smaller than the plotting symbol. The
 676 HST spectra demonstrate the broad band at 260 nm discussed by Noll et al. (1997).

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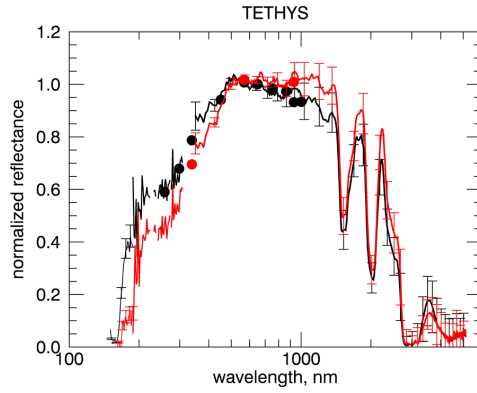
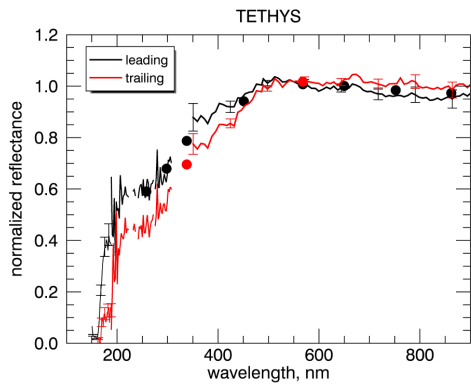
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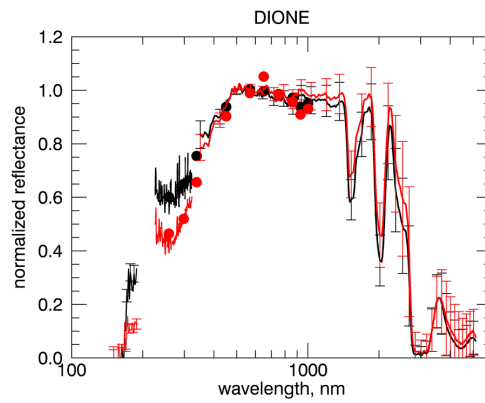
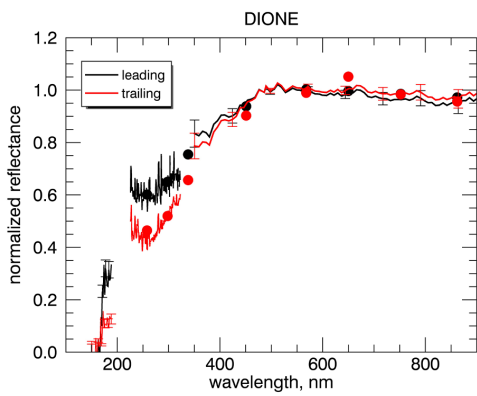
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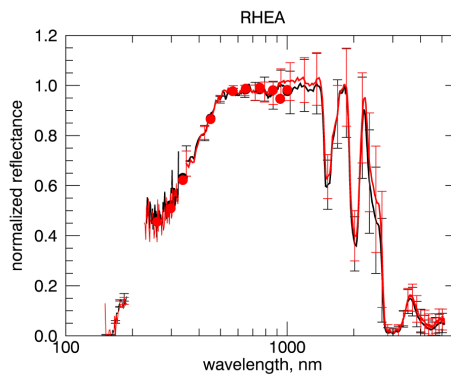
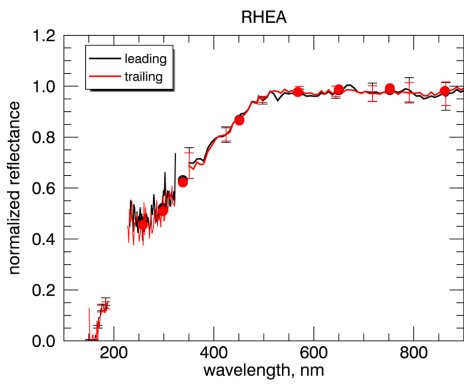
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686 **Figure 2.** Reflectance spectra, normalized near 600 nm, to directly compare leading and

687 trailing hemispheres of Tethys, Dione and Rhea.

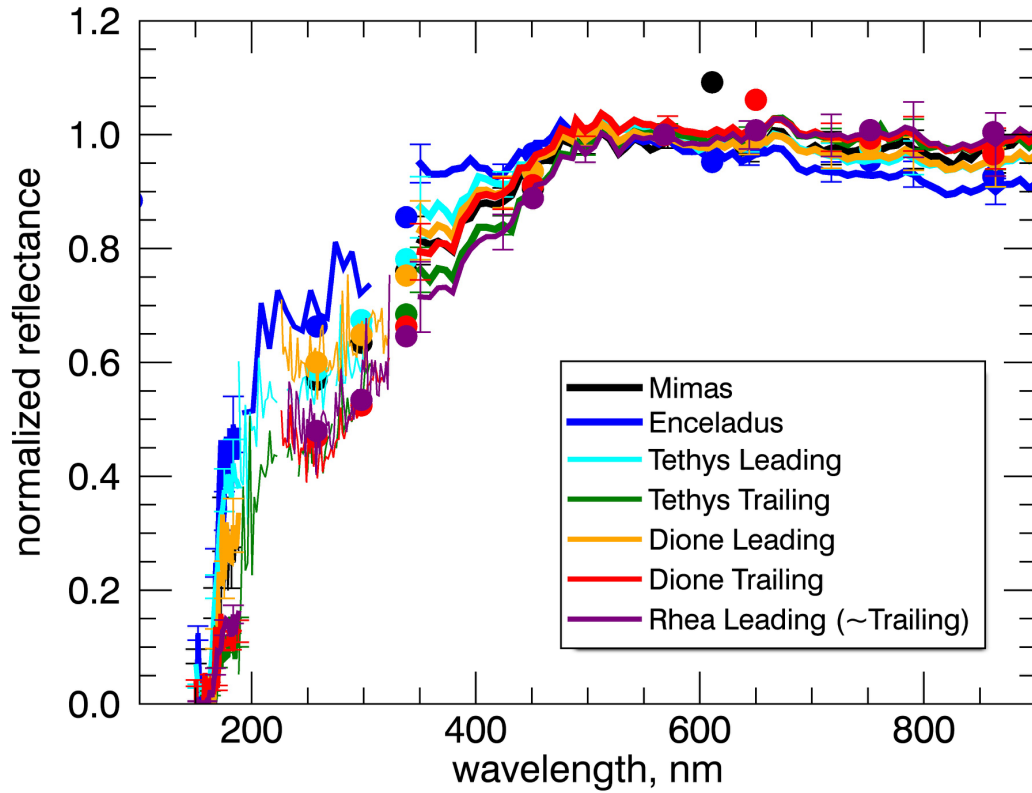
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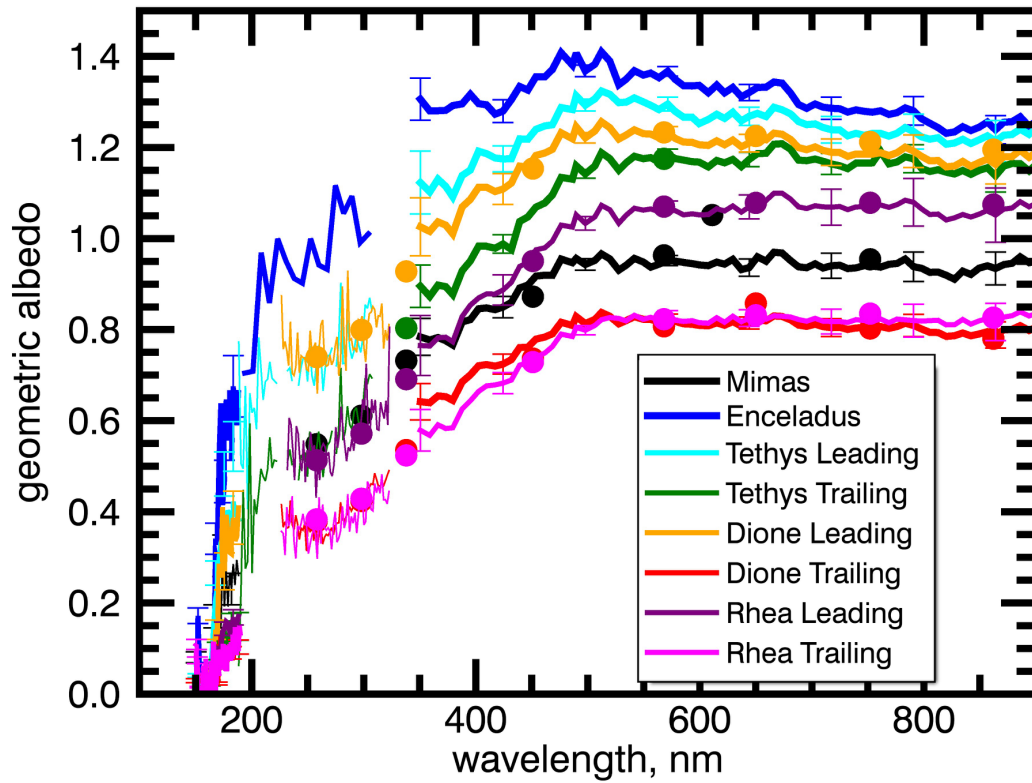
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694 **Figure 3.** Normalized composite spectra of all satellites using data from UVIS, ISS, HST
695 and VIMS. The UV absorption edge that begins at ~500 nm is strongest for Rhea, the
696 trailing hemispheres of Dione and Tethys, and possibly Mimas; it is least strong for
697 Enceladus and the leading hemispheres of Dione and Tethys. Most of the Mimas data are
698 hidden by Dione Leading data.

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701 **Figure 4.** Composite geometric albedo spectra of the Saturnian satellites. To generate
 702 these curves, we scale the normalized spectra of Fig. 3 by the visible geometric albedos
 703 in Table 2 (from Verbiscer et al., 2007). For Mimas and Enceladus we use average values
 704 of 0.963 and 1.376, respectively. Error bars on ISS data are smaller than the plotting
 705 symbols.

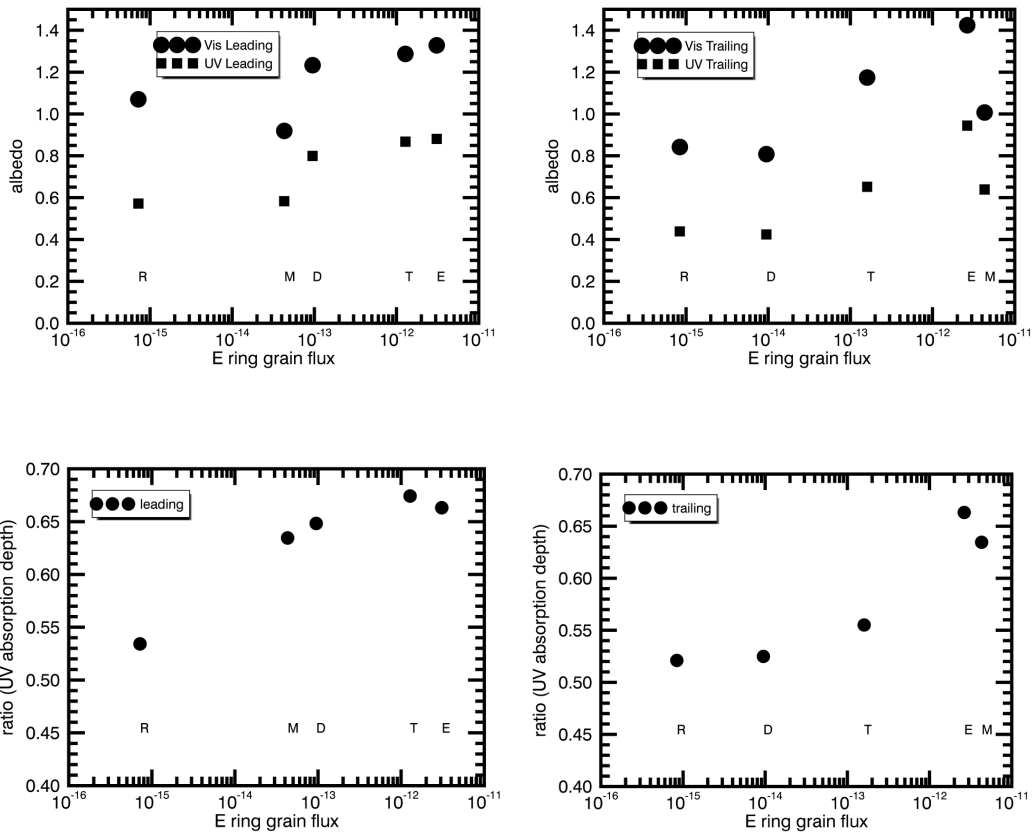
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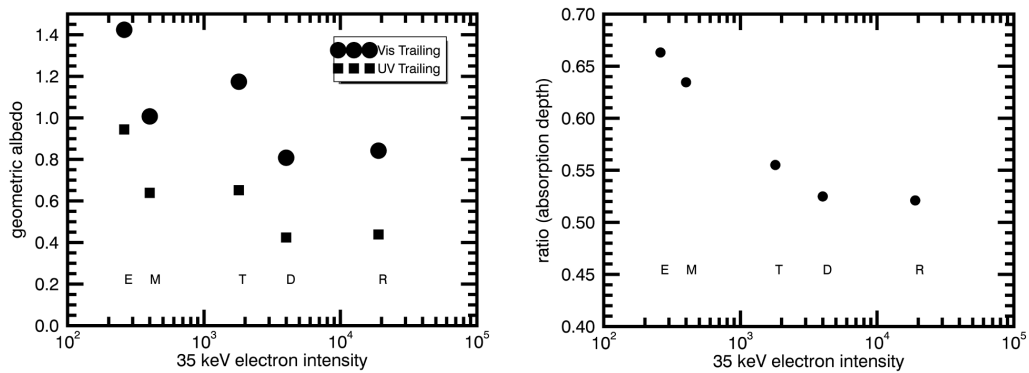
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713 **Figure 5.** Geometric albedos (at 300 nm and 600 nm, from Fig. 4) and UV absorption
 714 depth (where the UV absorption is given by the ratio of the albedo at 300 nm to the
 715 albedo at 600 nm) are plotted against E ring grain flux on the leading and trailing
 716 hemispheres. Horizontal axis units are $g/m^2/s$. On the leading hemisphere (left), there is
 717 an association between E ring grain flux and albedo; the correlation is stronger (with
 718 lower chi-squared fit values) than on the trailing hemisphere (right). On both leading and
 719 trailing hemispheres, there is a relationship between UV absorption and E ring grain flux,
 720 with UV absorption increasing with decreasing flux.

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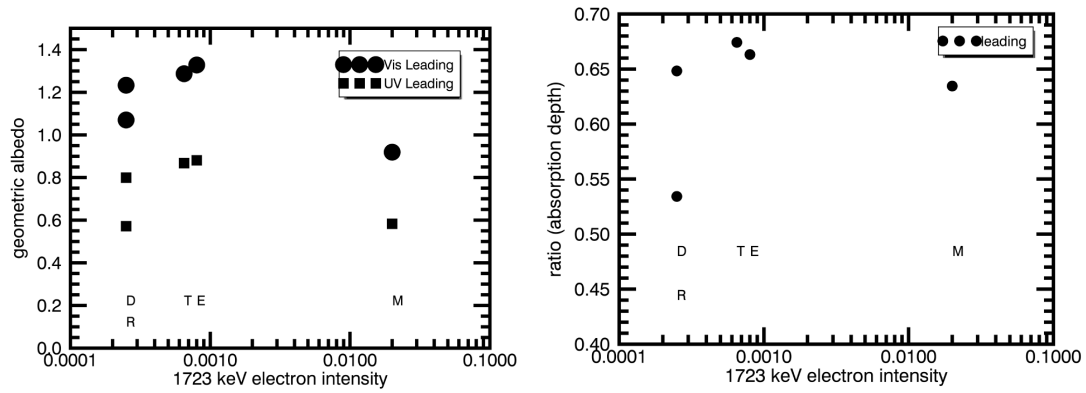


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724 **Figure 6.** Trailing hemisphere albedo (at 300 nm and 600 nm, from Fig. 4) and UV
725 absorption vs. electron intensity, where the UV absorption depth is given by the ratio
726 of the albedo at 300 nm to the albedo at 600 nm. Horizontal axis units are electrons
727 $\text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ keV}^{-1}$. (top left) The trailing hemisphere UV and visible albedos roughly
728 decrease as electron intensity (tens of keV) increases. (top right) The UV absorption on
729 the trailing hemisphere increases with 35 keV electron intensity; the UV absorption is
730 similar for Tethys, Dione and Rhea, suggesting some level of saturation. These plots use
731 35 keV electron intensity (Paranicas et al., 2011) as a proxy for ~tens of keV electrons,
732 which primarily impact the trailing hemispheres.

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736 **Figure 7.** In contrast to the ~tens of keV electrons shown in Fig. 6, ~MeV electrons
 737 (Kollmann et al., 2011) (which impact the leading hemispheres) do not demonstrate a
 738 coherent relationship with albedo (**left**) or UV absorption depth (**right**).

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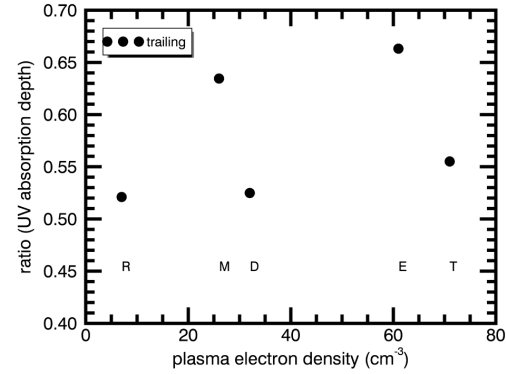
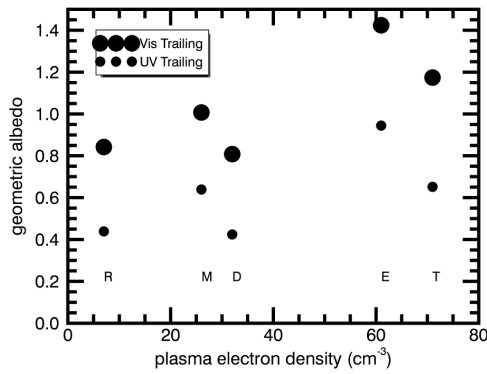
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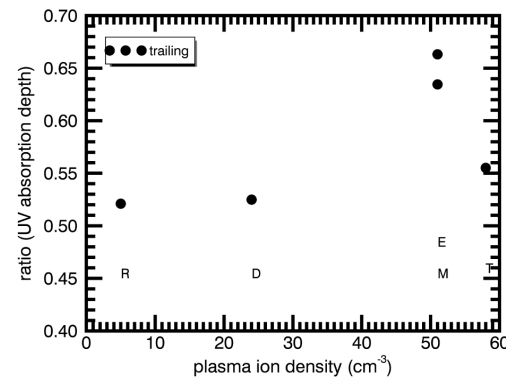
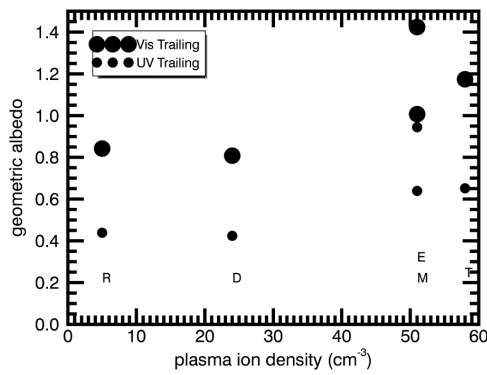
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750 **Figure 8.** In contrast to the ~tens of keV electrons shown in Fig. 6, cold plasma electrons
 751 (Persoon et al., 2006) (**upper**) and cold plasma ions (Persoon et al., 2009) (**lower**) (both
 752 of which impact the trailing hemispheres) do not demonstrate a coherent relationship with
 753 albedo (**left**) or UV absorption depth (**right**).

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