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1 **First Results from *Cassini*'s Flybys of Saturn's Ring Moons at the End of Mission**

2 This paper discusses the preliminary results from 6 Cassini instruments of 5 “closest ever” flybys
3 of Pan, Daphnis, Atlas, Pandora, and Epimetheus to show the surface properties of these moons
4 are determined by two competing processes: accretion of a red chromophore from Saturn's main
5 ring system and of icy particles from Enceladus

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39 **Five “best ever” observations of Saturn’s ring moons Pan, Daphnis, Atlas, Pandora, and**
40 **Epimetheus were obtained between December 2016 and April 2017 during the Ring-grazing**
41 **Orbit period of the *Cassini* mission. Unprecedented views of the moons’ morphology, structure,**
42 **particle environment, and composition were returned, as well as first detections in the**
43 **ultraviolet and thermal regions of the spectrum. The optical properties of the moons’ surfaces**
44 **are determined by two competing processes: contamination by a red chromophore in Saturn’s**
45 **main ring system, and accretion of bright particles from the E-ring originating from Enceladus’s**
46 **plumes.**

47
48 **Introduction**

49 Saturn possesses a family of small inner irregular moons that occupy dynamical regimes unique
50 to the system. Two moons orbit in gaps within Saturn’s main ring system: Daphnis, which was
51 discovered by the *Cassini* spacecraft in 2005 orbiting in the A-ring’s Keeler gap (1), and Pan,
52 which is found in the Encke gap in the A-ring (2). Three other “shepherd” moons orbit at the
53 edges of the A-ring (Atlas) or the F-ring (Pandora and Prometheus). Finally, the “co-orbital”
54 moons Janus and Epimetheus share horse-shoe orbits outside the F-ring and swap their positions
55 every four years (supplementary materials). Saturn’s rings are almost certainly tied to the origin
56 and continued existence of these moons. The main questions include whether the rings formed
57 from the break-up of an inner moon; if the moons formed from the consolidation of existing
58 rings, either primordial or impact-created; and the identity of key alteration processes acting on
59 the rings now and in the past. The main rings were originally considered unconsolidated
60 primordial debris, unable to form a moon because of tidal forces. Evidence from the two
61 Voyager spacecraft suggested the rings and inner moons were both debris from the breakup of

62 the same parent body, or perhaps of several parent bodies, with the moons being the largest
63 fragments from the collision (3). *Cassini's* discovery of low bulk densities for the moons along
64 with dynamical studies and the existence of ridges around the equators of Atlas and Pan
65 suggested the subsequent accretion of main ring particles onto these moons (4-6).

66

67 Analysis of the optical properties of the moons including color, albedo, and spectral properties in
68 the visible and infrared between 0.35 and 5.2 μm showed that they resemble the ring systems in
69 which they are embedded or abut (7-10). An elusive low-albedo reddish chromophore that could
70 be organic material, silicates, or nanophase iron (11), and that appears to be abundant in the rings,
71 tinged the moons, a finding that further supported a common origin for them and continuing
72 accretion of particles onto the moons' surfaces. The interactions of the ring system of Saturn with
73 its inner moons may form two distinct zones: an inner region in the vicinity of the main ring system
74 that is dominated by a red chromophore, and an outer region that is dominated by fresh, high
75 albedo icy particles from the E-ring. Complicating the picture, however, is the possible influence
76 of interactions with magnetospheric particles, which were shown to alter the color and albedo of
77 the main moon system of Saturn (12,13). Another key question is whether any volatiles other than
78 water ice exist on the ring moons. Were a molecule with higher volatility than water ice to be
79 found, it would point to material originating in a colder region outside the Saturnian system: the
80 discovery of CO_2 on Phoebe, for example, suggested this outer irregular moon originated in the
81 Kuiper Belt (14).

82 The last phase of *Cassini's* mission began on November 30, 2016 and ended on September 15,
83 2017, with two distinct periods: the "Ring-grazing" (or F-ring) Orbits, when 20 close passes to the
84 F-ring were accomplished, and the Proximal Orbits (the "Grand Finale"), when 23 dives between

85 the planet and the main ring system were executed. During the Ring-grazing Orbits there were
86 five “best-ever” flybys of Pan, Daphnis, Atlas, Pandora, and Epimetheus. Data were obtained by
87 the four remote sensing instruments on *Cassini*: The Imaging Science Subsystem (ISS; 15); The
88 Visual Infrared Mapping Spectrometer, with medium resolution spectra between 0.35 and 5.1 μm
89 (VIMS; 16); The *Cassini* Infrared Spectrometer (CIRS; 17); The Ultraviolet Imaging Spectrometer
90 (UVIS; 18); and *Cassini*’s fields and particles experiments, two of which obtained simultaneous
91 data that are described in this paper, the Cosmic Dust Analyzer (CDA; 19) and the Magnetosphere
92 Imaging Instrument (MIMI; 20). In this paper we discuss the first results from the closest flybys
93 of these moons, the details of which are summarized in Table 1. In addition to the “closest-ever”
94 flyby of Epimetheus on January 30, 2017, a second flyby of this moon, which was also better than
95 any previous event, occurred on February 21, 2017, with a closest approach of 8088 km. Valuable
96 data on the dust and plasma environment in the vicinity of the small inner moons was also captured
97 by the particles experiments during the subsequent Proximal Orbits.

98 [Table 1 here]

99 **Geology and morphology**

100 Previous images of the ring moons showed distinctive equatorial ridges on Pan and Atlas (4,5)
101 which were interpreted as likely formed by accretion of ring particles. Images of Daphnis were
102 ambiguous as to the morphology of any near-equatorial ridge. Previous images also showed the
103 small satellites all in synchronous rotation (6), but those at different distances from Saturn had
104 distinctive properties. Prometheus and Pandora’s orbits straddle the F-ring, and although they
105 exhibit different surface morphology, their densities are nearly identical (Table 2). The small (< 5
106 km mean radius) satellites Aegaeon, Methone, and Pallene that orbit in diffuse rings or ring arcs
107 (21, 22) have smooth ellipsoidal shapes indicative of hydrostatic equilibrium (6). The co-orbital

108 satellites, Epimetheus and Janus, by far the largest of the inner small moons, were found to have
109 nearly identical mean densities (Table 2), also the highest among the inner small moons. Grooves
110 had been observed on Epimetheus (23), and there were suggestions of discrete crater-filling
111 sediments on both Janus and Epimetheus (6). Epimetheus was observed well enough to establish
112 a ~7 deg. forced libration (24).

113

114 At the start of the Ring-grazing Orbits, the major puzzles concerning these objects included: Do
115 the differences among the ridges on Pan, Daphnis, and Atlas help constrain their origins and
116 evolution? What structural features are present on these moons, and can they reveal formation or
117 modification history? How is material moved across the surfaces? Are their compositions related
118 to their orbital positions? The six flybys at the end of the *Cassini* mission provided unprecedented
119 spatial resolution and new spectral information on the embedded ring moons to answer some of
120 these questions.

121

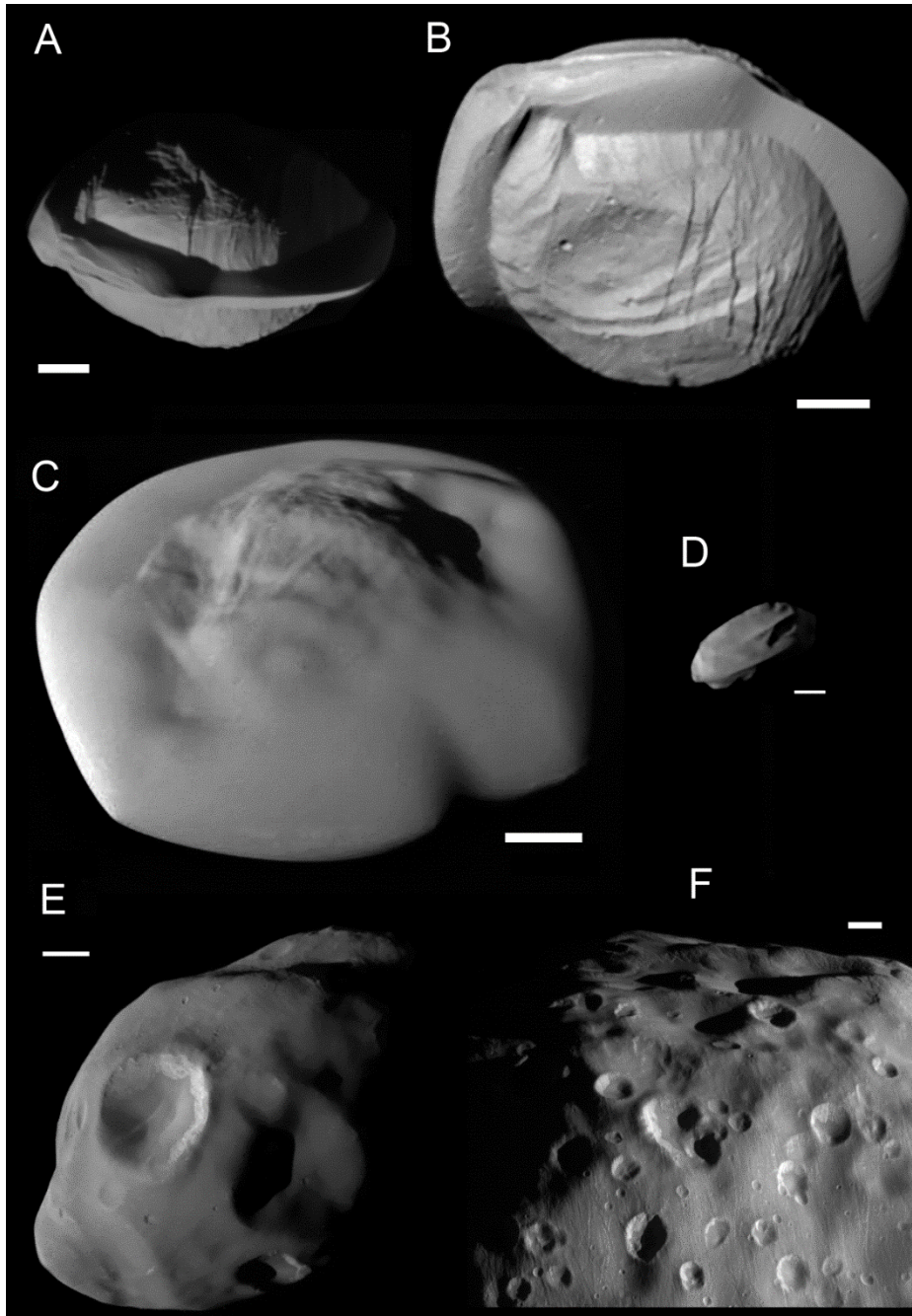
122 Table 2 provides the best measures of the shapes, volumes, and calculated mean densities of the
123 small satellites of Saturn. The late-orbit image data reduced uncertainties in volume and mean
124 density. Only Epimetheus and Janus have densities significantly above 500 kg m^{-3} ; the lowest
125 possible mean densities of ring satellites are below 300 kg m^{-3} . Surface accelerations vary
126 substantially across each object due to shapes and especially tidal accelerations (Table 2).

127 [Table 2 here]

128 *Main Ring moons and ridges*

129 The high resolution data make clear that the equatorial ridges on Pan and Atlas are distinct from
130 what appears to be a more structurally competent “core” of each moon, and that ridges are different

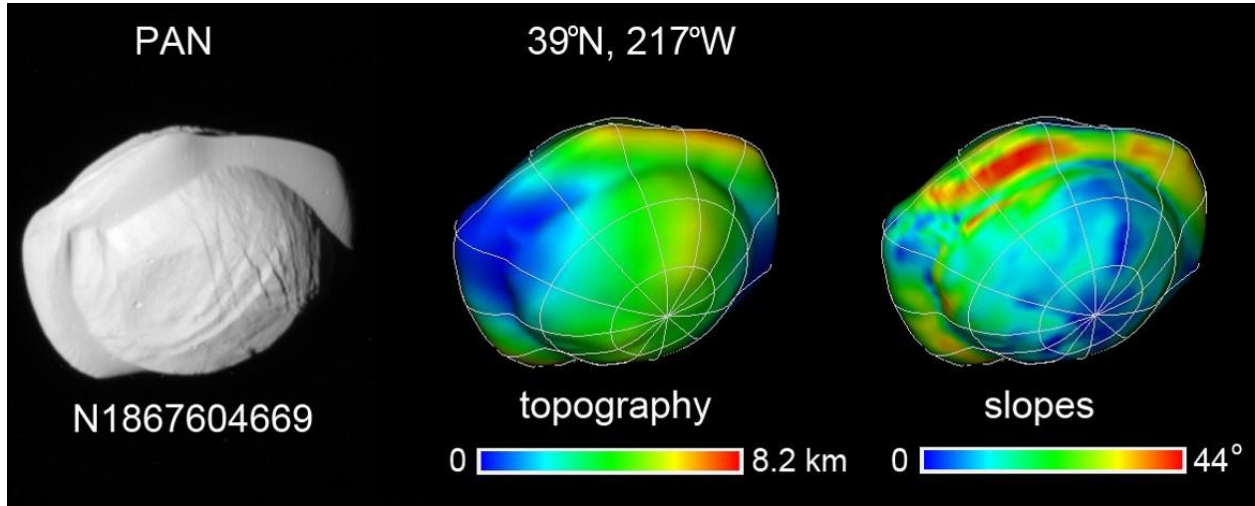
131 on all three main ring satellites. The fractional volumes of the ridges are Pan ~10%; Daphnis ~1%,
132 and Atlas ~25%. Atlas's ridge is smooth at 76 m/pixel, with some elongate to irregular brighter
133 albedo markings. It grades into a core with distinct ridge and groove topography (Fig. 1.), with a
134 slightly polygonal equatorial profile previously known (6). Pan's ridge has distinct topographic
135 margins with the core, with a somewhat polygonal equatorial shape, and it has some grooves, small
136 ridges, and even some small impact craters. Meridian profiles across Pan's ridge vary considerably
137 with longitude. Fig. 2 shows Pan in the best northern view, with calculated relative gravitational
138 topography and surface slopes. Pan's ridge is not the result of material sliding toward areas made
139 low by rotation and tides as are some ridges on small asteroids (27, 28) as slope directions are not
140 latitudinally directed. The distinct boundary between ridge and core, the distinct surface
141 morphology on each, and the large differences in relative heights along the ridge require the
142 formation of this ridge to be unrelated to surface, gravity-driven processes. These observations
143 are consistent with formation of the ridge by accretion of particles, the pattern being dictated by
144 the relative orbital and rotational dynamics of the core and ring particles (4).



145
 146 Fig 1. **Ring moons.** (A) Pan, N1867606181, from 26°S. Scale bar 5 km. Obtained at 182 m/pixel
 147 (m/p). (B) Pan, N186704669, from 39°N; scale bar 5 km; 147 m/p. (C) Atlas, N1870699087, from
 148 40°N; scale 5 km; anti-Saturn point at lower left; 108 m/p. (D) Daphnis, N1863267232, from 14°N;
 149 anti-Saturn point to left; scale 2 km; 170 m/p. (E) Pandora N1860790629 Scale bar 10 km. Sub
 150 spacecraft point is 35°N,98°W; north pole is close to two small craters above large, bright-walled

151 crater; 240 m/p. (F) Epimetheus. N1866365809; Grooves and craters dominate the surface. Scale
152 5km; 99 m/p. (The N numbers are the image identifiers.)

153
154



155
156

157 Fig. 2. **Relative topography and slopes on Pan.** Topography is relative potential energy at
158 surface due to assumed homogeneous interior density, rotation, and tides, divided by an average
159 surface acceleration. Slopes are angles between surface normals and net acceleration vectors
160 (negative).

161

162 The nominal mean densities of all three main ring moons give calculated surface accelerations
163 near zero at the sub- and anti-Saturn points. The remainder of all the surfaces has inward directed
164 net accelerations. These results suggest the ends may be limited by their ability to accrete
165 materials, but there is much to be explored in the dynamics of accreting and/or modifying these
166 ridges.

167

168 The surfaces of the ring moons may be crudely divided into three units on the basis of morphology,
169 geography, and texture of surface visible at the available resolutions (Fig. 3). The equatorial ridges
170 generally have smoother surfaces than do the “cores.”

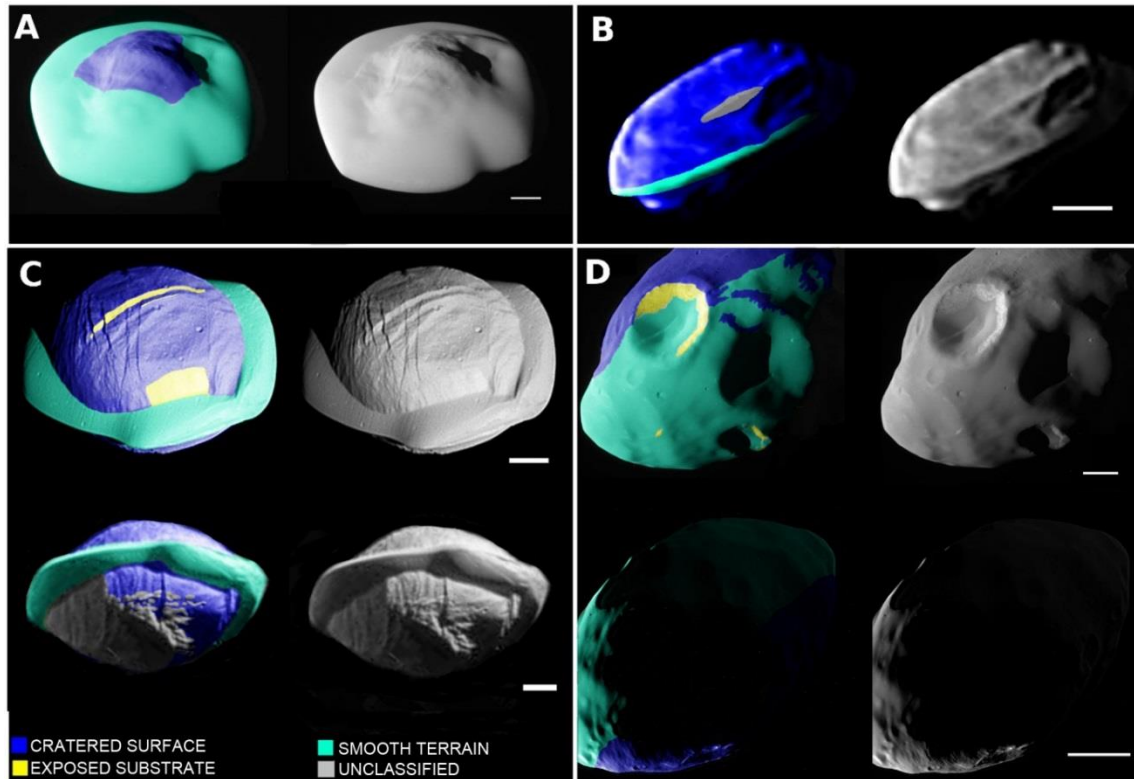
171

172 The cores have more impact craters than do the ridges on Pan and Atlas which display a few sub-
173 kilometer impact craters. Pan and Atlas’ cores show lineated topography indicative of body
174 structure. Pan has two distinct global sets of quasi-parallel faults, one of which is roughly
175 concentric to the long axis and exhibits conspicuous scarps and terracing from likely equatorward
176 displacements. Axial symmetry of this system suggests that tidal forces were involved in its
177 development. The second system trend is oblique to the first, and is well expressed in both north
178 and south hemispheres (Figs.1, 3). By contrast, Atlas’ core exhibits patterns of elongated ridge
179 and groove topography that do not have fault scarp morphology, and appear covered by at least
180 tens of m of loose regolith.

181

182 Pan’s equatorial ridge is thickest north-south at longitudes of approximately 220°, 310°, 135°, and
183 50° W, yet its radial extent peaks at longitudes of 5°, 55°, 100°, 180°, 235°, and 310°. It supports
184 grooves and small craters: their presence suggests some cohesion in this extreme low-g
185 environment. Atlas’ equatorial profile is also somewhat polygonal, but not as pronounced as
186 Pan’s.

187



188
 189 **Fig. 3. Distribution of three primary units on ring moons** (A) Atlas, scale bar 5 km. Obtained
 190 at 94m/pixel (m/p). (B) Daphnis, scale bar 2km; 167 m/p. (C) Pan scale bars 5 km; 144 m/p (top)
 191 and 279 m/p (bottom). (D) Pandora (top scalebar, 10km, bottom, 20 km); 137 m/p (top), 200 m/p
 192 (bottom). Cratered surface: heavy cratering, relatively crisp surface relief, and regolith typical of
 193 other small bodies in the Saturnian system. Smooth terrain: distinctly smooth compared to typical
 194 small body cratered surfaces; some is material collected in crater floors. Exposed substrate:
 195 relatively bright with lineations more typical of rigid materials than of loose regolith. Unclassified
 196 materials are those for which insufficient data are available to resolve ambiguities between terrain
 197 types.

198
 199 The classification of some material units on Pan's southern hemisphere is ambiguous, in part
 200 because more of these regions are illuminated only by Saturnshine. These currently unclassified

201 units in Fig. 3 include knobby streaks of hummocky material that trend approximately parallel to
202 the equator and hummocky deposits that outline a curvilinear depression on the Saturn-facing side.

203
204 The best-available spatial resolution of Daphnis imaging is poorer, 170 m/pixel vs. that of Pan
205 (147 m/pixel) and Atlas (76 m/pixel), and Daphnis is only about a quarter the dimensions of the
206 other ring moons. As a result, it is not clear that its near-equatorial ridge is any smoother or
207 otherwise different from the rest of the satellite surface. The equatorial ridge extends at least from
208 75°W to 185°W. An additional ridge at 22°N runs from ~ 60°W to 120°W. Both ridges are 300-
209 400m north-south, and perhaps radially 300 m in extent. The core has an elongated (2.5 km)
210 depression that is roughly aligned east-west.

211
212 *F-ring moons*
213 Prometheus and Pandora orbit inside and outside the F-ring. The higher resolution achieved on
214 the Pandora flyby provided better coverage of the geography of grooves and debris on the surface
215 of this “shepherding” moon (Fig. 1). Although many of the grooves form a familiar pattern
216 concentric to the major axis of the body, there is a slight offset of the pattern especially noticeable
217 on the sub-Saturn side, which reflects the orientations mapped earlier (21).

218
219 ISS closeup images of Pandora revealed that part of the leading hemisphere seen in Fig. 1 is smooth
220 in comparison to other regions of Pandora (Figs. 1,3). The smooth deposits are most continuous
221 near the equator but they become patchy at high latitudes where they appear to be too thin to mute
222 the coarse surface relief along protruding crater rims. The smooth deposits extend approximately
223 $\pm 60^\circ$ in latitude, most like the broad extent of the ridge on Atlas. This arrangement might indicate

224 the accretion of material as on the main ring moons. If so, its efficacy on Pandora is at least two
225 orders of magnitude smaller than on Pan and Atlas, and much broader latitudinally. However,
226 variations in resolution, illumination, and viewing geometry make mapping of textural variations
227 on Pandora ambiguous.

228

229 *Co-orbitals*

230 The highest resolution images of the flybys were of Epimetheus, the smaller of the co-orbitals,
231 reaching scales of 36 and 49 m/pixel. These data greatly enhanced mapping of grooves and
232 sediment coverings, both seen in lower resolution data (23). The grooves are global in occurrence,
233 and are largely the typical beaded to straight, elongated depressions that appear to be features
234 formed in loose regolith. There are some exposures of brighter material apparently devoid of
235 regolith cover (Fig. 1F) that also show elongate lineations, generally slight depressions. These
236 align with the grooves nearby that appear to be regolith features, and largely align with the regolith
237 groove global patterns. This association appears to support a relation of at least some regolith
238 grooves to fractures or other structures in a more rigid underlying “bedrock,” although the variety
239 of groove morphologies on many objects suggest grooves may have a multiplicity of origins (29,
240 30, 23, 31). The highest resolution images also show exposures of crisscrossing linear ridges and
241 other lineations. If representative of the interior, these features suggest structure and history far
242 different from simple accumulation of a “rubble pile.”

243

244 *Colors of the Small Ring Satellites and Pandora*

245 The whole-disk colors of the ring satellites as measured in ISS broadband filters (32) follow similar
246 trends with distance from Saturn as those found by the VIMS instrument (7-10). The ISS Narrow

247 Angle Camera (NAC) uses paired broadband filters. The CL1:UV3 pair (341 nm) and CL1:IR3
248 pair (930 nm) span the spectral range of the camera, and IR3/UV3 ratios can represent the ratio
249 of observed brightness values in each of the broadband filters (cf. 6). For reference, Enceladus,
250 the presumed source of ice particles that mute colors on other satellites, has an effectively neutral
251 IR3/UV3 ratio of 1.03 ± 0.02 (33).

252
253 Pan, Daphnis, and Atlas are expected to show effects of material deposited from the rings. Closest
254 to Saturn, Pan's average IR3/UV3 ratio of 2.5 ± 0.2 is red but significantly smaller than the value
255 of 3.3 ± 0.2 of the adjacent A-ring (i.e., it is less red than the rings). Further out, the A-ring
256 IR3/UV3 ratio decreases from 2.7 ± 0.2 on the inside of the Keeler gap (which contains Daphnis)
257 to 2.2 ± 0.3 on the outside. The mean value is not statistically different from the value of 2.3 ± 0.3
258 of Daphnis itself. The equatorial ridges on the ring satellites may be very old (4) but the colors
259 most likely reflect a patina of material deposited from geologically recent and ongoing processes.
260 Atlas, which falls just outside the A-ring has an IR3/UV3 ratio 2.4 ± 0.1 . Pandora, with its value
261 of 1.9 ± 0.1 , is close to the F-ring further from Saturn. It lacks an equatorial ridge but possesses
262 smooth deposits which on the leading side extend from the equator to mid-latitudes.

263 Among the terrains shown in Fig. 3 color differences can be identified from the high-resolution
264 images on all but Daphnis, for which the CL1:UV3 images were badly blurred by spacecraft
265 motion. The IR3/UV3 ratio for cratered materials on Pan is about 19% higher than for its equatorial
266 ridge and is most like the average global value. Similarly, the ratio for cratered materials on Atlas
267 is about 16% higher than for its ridge, but in this case, the global average value not surprisingly
268 most closely matches that for Atlas' larger equatorial ridge. For Pandora, the cratered materials
269 have a IR3/UV3 ratio that is 15% *lower* than for the smooth materials towards the equator. The

270 global average ratio is in between that for the cratered material and the smooth deposits. Exposed
271 substrate is visible as a scarp on Pan and a bright exposed crater wall on Pandora. On Pan, the
272 IR3/UV3 ratio of exposed substrate is intermediate between the ridge materials and crater
273 materials. However, on Pandora, the corresponding ratio for the exposed crater wall is not
274 statistically distinguishable from that of the cratered material.

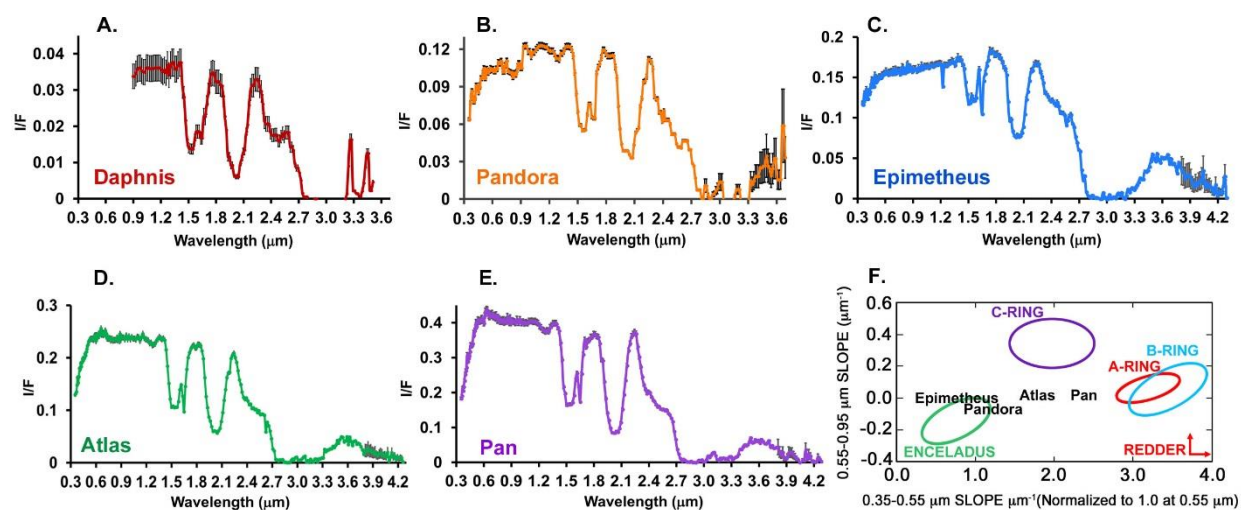
275 **Composition**

276
277 Most of the compositional information on the surfaces of Saturn's moons has been obtained by
278 VIMS (16).

279 Prior to the close flybys of the ring moons, some spectra were gathered by VIMS and rudimentary
280 compositional information was obtained (7-10). Water ice was the only volatile identified, but the
281 moons' visible colors varied, especially in the 0.35-0.55 μm spectral region, which suggested
282 contamination by a reddish chromophore that perhaps came from the ring system itself. The
283 identity and source of this chromophore was one of the main questions still remaining at the final
284 stages of the *Cassini* mission. (This coloring agent is distinct from the low-albedo red material
285 from the Phoebe ring that is deposited on the leading hemisphere of Iapetus and on Hyperion (7,
286 8).)

287 The close flybys of the embedded moons Daphnis and Pan enabled the acquisition of spectra of
288 these moons for the first time, although only an IR spectrum (1.0-5.0 μm) for Daphnis was
289 successfully obtained. These new data provide a key test for the origin of the red chromophore in
290 the inner Saturnian system. These observations also provide rudimentary information on spatial
291 variations in composition on the moon's surfaces, although the resolution is only about 1-2%
292 (depending on the instrument mode) of ISS's (supplementary materials)

293 Fig. 4 shows the spectrum of each moon from 0.35-5.0 μm (1-5.0 μm for Daphnis). The only
 294 spectral absorption bands detectable in these images are the water ice bands at 1.25, 1.6, 2.0 and
 295 3.0 μm . No other volatiles are detectable, including CO_2 , although its prime absorption band in
 296 this spectral region is at 4.26 μm , which is in the noisy region of the spectrum beyond about 3.5
 297 μm . One interesting feature of these spectra is the relatively large depth of the absorption band
 298 for crystalline water ice at 1.65 μm . This spectral band is sensitive to radiation damage (34); its
 299 unusual depth implies a lack of this type of damage in the ring environment, which is expected
 300 given the dearth of high-energy particles in the rings (see the section on particle observations).
 301 Water ice spectral bands are also sensitive to grain size, with deeper bands signifying larger sizes
 302 (35). A larger particle size could signify larger regolith grains in the main ring system than in the
 303 E-ring, or it could simply be due to gravitational escape of the smaller particles, some of which
 304 could be formed by continual impacts.



305
 306 Fig. 4A-E. Spectra of the five moons from 0.35-5.1 μm . 5F The colors of Saturn's main ring
 307 system and Enceladus (7,8) compared with those of Epimetheus, Atlas, Pandora, and Pan.
 308 There is a gradient depending on the position of the moon with respect to the rings, with Pan,

309 which is embedded in the Encke gap, being the reddest and Epimetheus, which is farthest from the
310 rings and closest to Enceladus, being the bluest. This effect results from the countervailing
311 processes of contamination by a red chromophore from the main rings and ice particles from the
312 E-ring, which is formed from particles from Enceladus.

313 The VIMS visible colors show good agreement with those derived by ISS with equivalent VIMS
314 numbers of the IR3/UV3 ratios of 2.7 ± 0.3 for Pan; 2.2 ± 0.2 for Atlas, 1.7 ± 0.2 for Pandora, and
315 1.5 ± 0.1 for Epimetheus (the VIMS spectrum extends to only $0.35 \mu\text{m}$: this value was used for
316 UV3 and the error bars adjusted accordingly). The moons embedded in the rings show important
317 spectral differences with the surrounding rings; in general they are less red (Fig. 5F). The VIMS
318 ratio image of Atlas shows uniformity between the main body and its equatorial ridge, at least in
319 water ice abundance, which implies accumulation of particles away from the equator to provide a
320 globally homogeneous surface. Color differences below the spatial resolution of VIMS may exist,
321 as detected by ISS in the visible.

322 The most striking difference among these new spectra is the difference in color measured by the
323 slope between 0.35 and $0.55 \mu\text{m}$. The new spectrum of Pan is extraordinarily red compared to
324 other Saturnian moons. Atlas, the shepherd moon just outside the A-ring, is also red but less so,
325 and Pandora, which is associated with the F-ring, even less. The color of Epimetheus is more like
326 that of the medium-sized moons (7-9). Thus, there is a gradient in color with distance from Saturn's
327 ring system, with the embedded Pan being the most red. This view is clear in Figure 5A-E, where
328 the slope of the visible spectrum increases sharply as the distance to Saturn increases, and it is
329 quantified in Fig. 5F, which shows the visible colors derived from the recent close flybys with the
330 colors of the main ring system of Saturn (8). These results imply the red chromophore comes from
331 the rings themselves. However, the differences in color between the moons and their adjacent rings

332 – the small moons are consistently bluer than their surrounding rings - could be due to another
333 contaminant: particles of almost pure water ice from the E-ring. This ring is a diffuse torus that is
334 fed from the plume of Enceladus. The particles have a wide range of orbital elements and
335 predominately impact the leading sides of the main moons (or the trailing side of Mimas) to alter
336 their albedo and color (36-38). The ring moons’ leading hemispheres would tend to be “painted”
337 by fresh grains and accrete more water ice than the surrounding ring particles.

338 The depth of the water ice band at 2.0 μm compared to the continuum at 1.8 μm (1.8/2.0 μm) is
339 $5.2 \pm 0.1 + 0.1$ for Pan, 5.0 ± 0.2 for Daphnis; 4.4 ± 0.1 for Atlas, 3.4 ± 0.1 for Pandora, and 2.4 ± 0.1 for
340 Epimetheus. The band-depths increase closer to Saturn, most likely due to the increasing particle
341 sizes (35). This view is consistent with the moons embedded in the ring (Pan and Daphnis) being
342 coated with main ring particles rather than with smaller particles from the E-ring. (The absorption
343 band at 1.6 μm shows a similar but weaker trend).

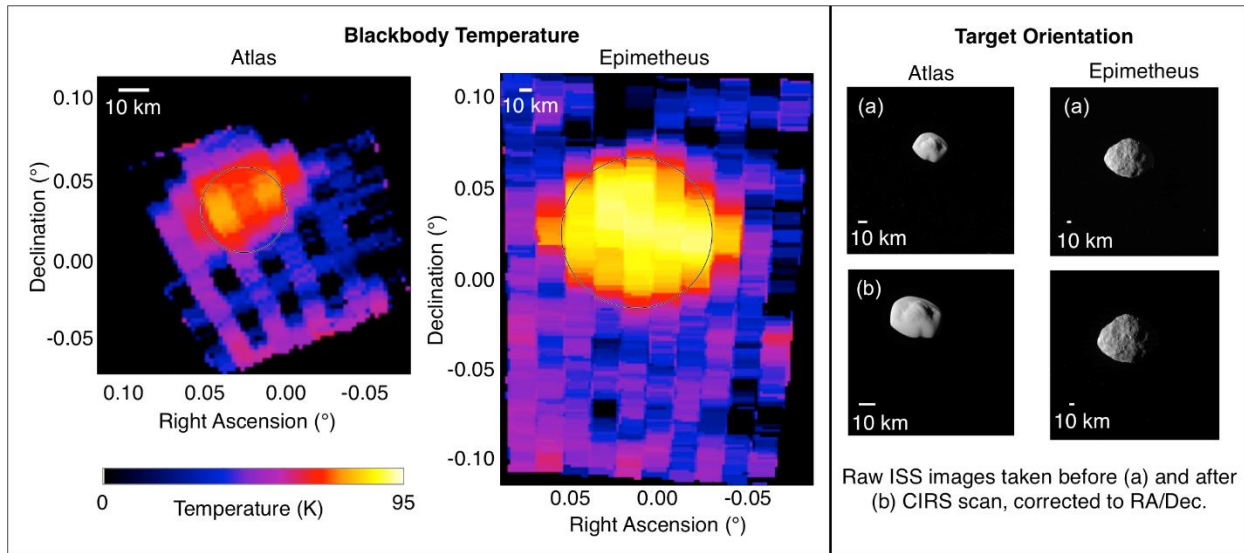
344 Interactions between moons and magnetospheric particles can also alter the moons’ colors and
345 albedos (12, 13). However, results from the fields and particles experiments in the vicinity of these
346 moons showed a dearth of high energy particles with the expectation that these alterations would
347 be slight (see below).

348 **First Ultraviolet and Thermal Infrared Detections of the Small Moons of** 349 **Saturn**

350 During the Ring-grazing Orbits the spacecraft was in a radiation and dust environment that resulted
351 in high background levels for UVIS. One successful detection was made of Epimetheus during
352 the encounter on Feb 21, 2017. Even on that flyby, the signal is only above the background for the
353 longest FUV wavelengths, $\sim 0.170\text{-}0.19 \mu\text{m}$. However, this single UV measurement of reflectance

354 places some constraints on surface composition and exogenic effects on Epimetheus. At 72° solar
355 phase angle (the angle between the spacecraft, Epimetheus, and the Sun), the derived normal
356 reflectance averaged between 0.17-0.19 μm is 0.09 ± 0.02 . For comparison, this number is roughly
357 1.5-2 times lower than the reflectance measured at Tethys under similar viewing geometry;
358 however, Tethys has a significantly higher visible geometric albedo (~ 1.2 compared to ~ 0.73 for
359 Epimetheus (36)), which indicates that Epimetheus may have a roughly uniformly lower
360 reflectance than Tethys in the UV-visible range. The UV-visible spectral slope and albedo are
361 strongly driven by exogenic effects, since this spectral range senses the uppermost layer of the
362 regolith affected by processes including radiolysis and E-ring grain bombardment. The UVIS
363 result combined with the knowledge of the visible albedo may suggest that Epimetheus is not as
364 affected by the brightening effects of the E-ring grains as Tethys is (36), or that there is some other
365 darkening agent or process important at Epimetheus's location. Thus, the UV-visible albedo of
366 Epimetheus may simply reflect the relative importance of the alteration by the reddish lower-
367 albedo chromophore and the icy E-ring particles at this moon's distance.

368 CIRS made positive detections of two moons: Epimetheus and Atlas (supplemental materials). The
369 results are given in Fig. 5, which shows the temperature that has a blackbody emission curve best
370 able to fit the observed radiance over all wavelengths. Both Epimetheus and Atlas are clearly
371 visible above the background dark sky. The mean surface temperature observed on Epimetheus is
372 90.1 ± 2.7 K, and 82.4 ± 4.7 K on Atlas.



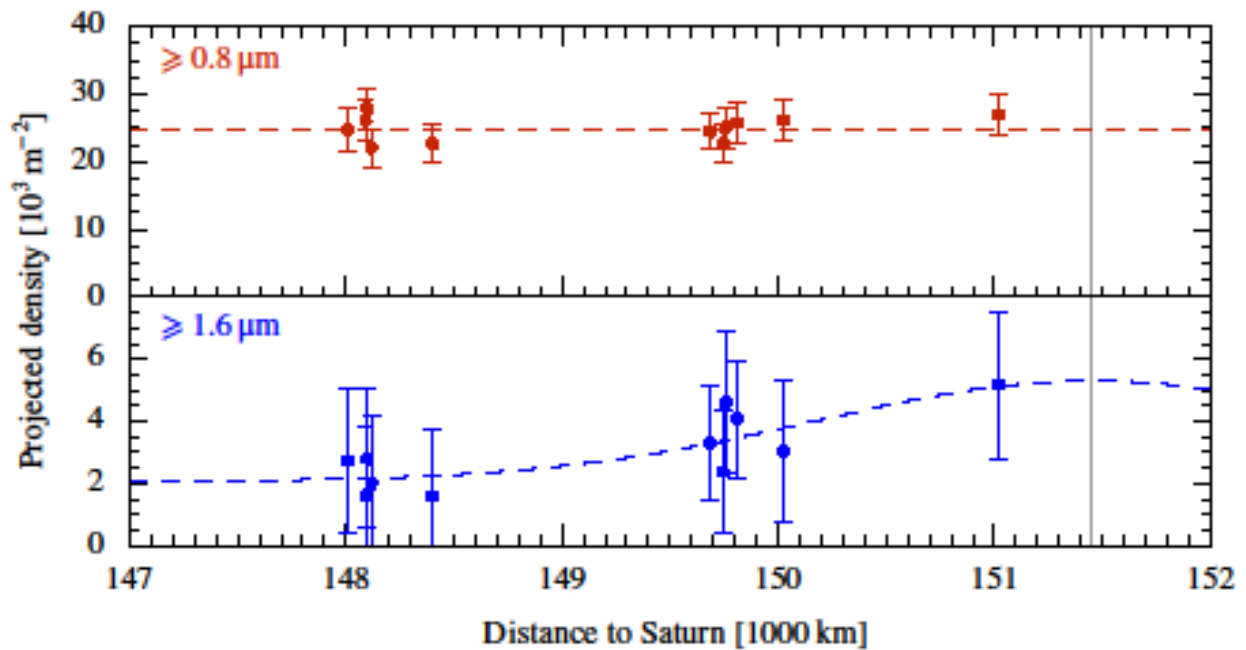
373
 374 Fig. 5. CIRS and ISS observations of Atlas and Epimetheus. Left: The blackbody temperature of
 375 the two targets, as determined by fitting a blackbody curve to the full CIRS radiance spectrum at
 376 each location. The results are shown in Right Ascension/Declination space, which has been
 377 corrected so the center of the target lies at $0^{\circ}/0^{\circ}$. Right: Raw ISS observations of both targets taken
 378 before and after the CIRS scan (supplemental materials).

379 Particle Observations

380 Throughout the Ring-grazing Orbits, the Particle and Fields experiments obtained unprecedented
 381 coverage of Saturn's plasma and dust environment, including detailed measurements of the region
 382 around the small inner moons. First results from the analysis of this data provide a basic
 383 understanding of whether the surfaces of these bodies are altered by the dusty plasma, and what
 384 effects the moons have on the environment, such as forming tori or cavities.

385 In the course of the Ring-grazing Orbits, *Cassini* passed close to the orbits of the co-orbital moons
 386 Janus and Epimetheus. During 11 of the 20 ring plane crossings, the High Rate Detector (HRD)
 387 of CDA detected in total about 2,000 dust grains with radii larger than $0.8 \mu\text{m}$. While the vertically
 388 integrated number density of grains smaller than $1.6 \mu\text{m}$ does not depend on the radial distance to

389 Saturn, the density of bigger grains drops by about 50% over a radial distance of approximately
 390 3500 km (Fig. 7). The larger particles are less susceptible to non-gravitational forces and, therefore,
 391 particles ejected from the moons stay closer to their parent bodies and form a more confined ring
 392 (39). The fit of a Gaussian distribution including the dust background from the F- and G-rings to
 393 the HRD data constrains the radial width of the ring (FWHM) to about 4,300 km leading to a total
 394 number of ring particles larger than $1.6 \mu\text{m}$ of $2 \cdot 10^{19}$.



395
 396 **Fig. 7. Radial density distribution obtained from Cassini CDA-HRD dust measurements.**
 397 While the density of the $> 0.8 \mu\text{m}$ sized particles can be well-fitted by a constant profile (red dashed
 398 line), the density of the $\geq 1.6 \mu\text{m}$ sized particles decreases inward from the orbit of Janus and
 399 Epimetheus. The dust distribution of the larger particles is modeled by a Gaussian distribution
 400 (blue dashed line) with a maximum at the mean radial position of Janus and Epimetheus (vertical
 401 gray line) including a constant background density.

402

403 Many dust rings are formed by ejecta from high-velocity impacts of interplanetary micro-
404 meteoroids eroding the surfaces of satellites without atmospheres. The measured particle number
405 in the Janus-Epimetheus ring constrains the poorly known parameters of the impact-ejection dust
406 creation model (40,41) at Saturn, although more recent work by CDA indicates a higher flux.
407 Using an unfocussed flux of $> 2.7 \cdot 10^{-16} \text{ kg m}^{-2} \text{ s}^{-1}$ with an impact speed of 4.3 km s^{-1} (42), the
408 dust production rate from both moons is about 0.91 kg s^{-1} . (0.64 kg s^{-1} from Janus and 0.27 kg s^{-1}
409 from Epimetheus). This corresponds to $9.8 \cdot 10^{11}$ particles larger than $1.6 \mu\text{m}$ per second ($6.9 \cdot 10^{11}$
410 s^{-1} from Janus and $2.9 \cdot 10^{11} \text{ s}^{-1}$ from Epimetheus) assuming a cumulative power law size
411 distribution $\propto s^{-\alpha}$ with $\alpha = 2.4$ and a maximal ejecta mass of $1 \cdot 10^{-8} \text{ kg}$ consistent with observations
412 of impact-generated dust clouds around the Galilean moons (43, 40).

413 To explain the measured number of ring particles, this comparably high production rate requires a
414 shallow slope of the cumulative ejecta velocity distribution $\propto v^{-\gamma}$ ($\gamma=1$), and a higher kinetic energy
415 dissipation than predicted by laboratory experiments (kinetic energy ratio of ejecta to impactor is
416 5%). This points to a highly dissipative and porous (snow or regolith) surface. With this result, we
417 find that most impact-ejecta are gravitationally bound to the moons and fall back to their surface,
418 while only about 6% of them escape to the ring. Numerical simulations reveal that most of the ring
419 particles are recaptured by Janus and Epimetheus after an average lifetime of 60 years resulting in
420 an estimate of $1 \cdot 10^{20}$ ring particles larger than $1.6 \mu\text{m}$. This is, considering the large uncertainties
421 of the impact-ejection model, in fair agreement with the observed value of $2 \cdot 10^{19}$.

422

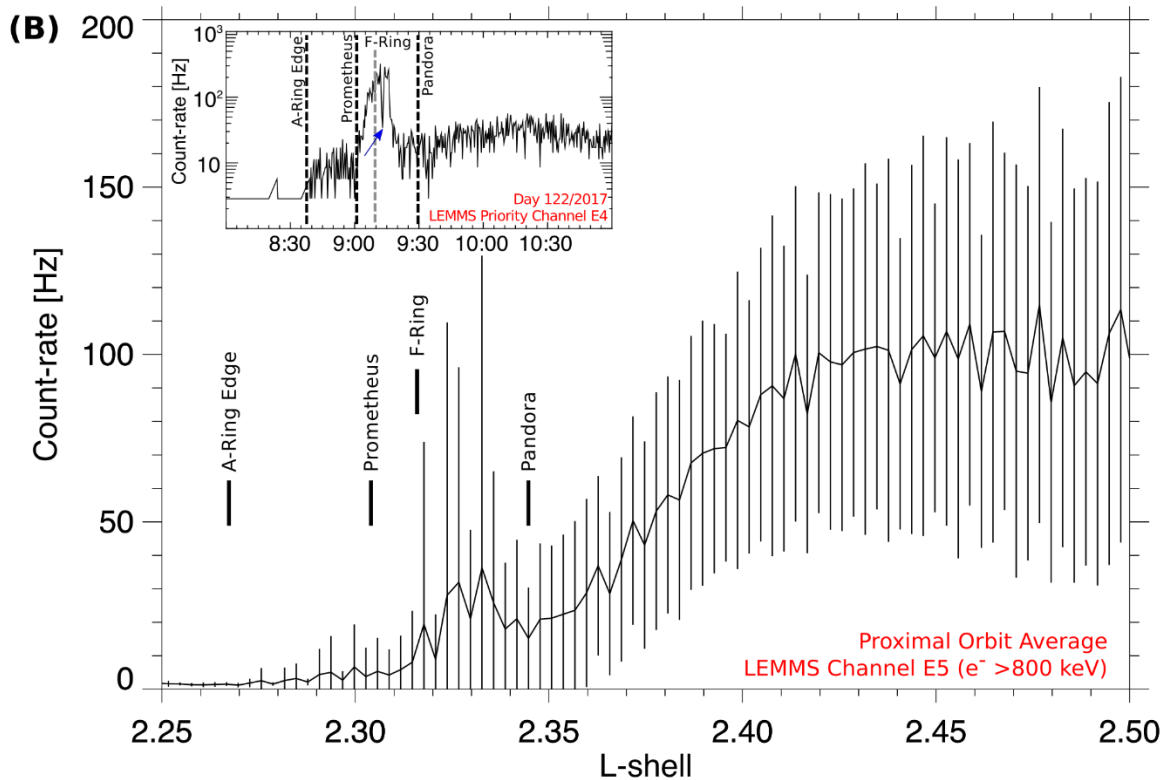
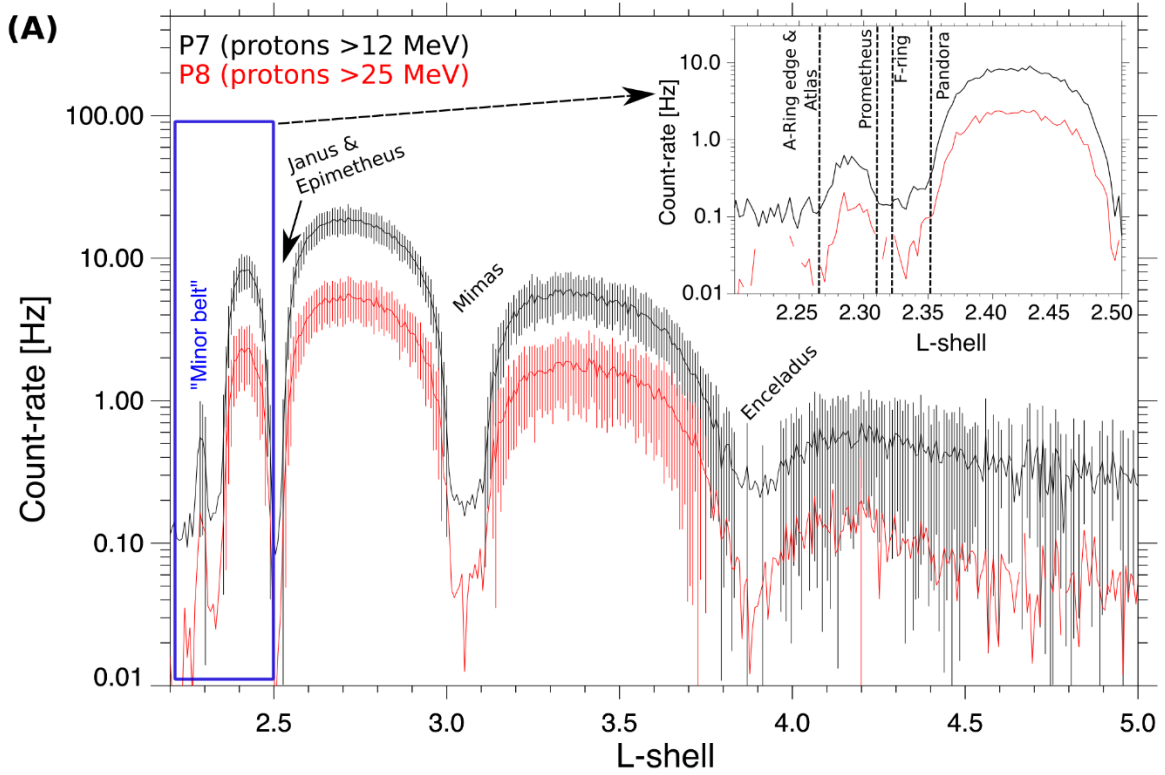
423 Additionally, the CDA Chemical Analyzer (8) has recorded spectra of submicrometer-sized dust
424 particles ($0.1 \mu\text{m} - 0.4 \mu\text{m}$). The compositional analysis of these spectra shows mostly ice grains

425 but also a few percent pure silicate grains or ice-silicate mixtures. The source of the icy particles
426 could either be the inner edge of the E-ring or surface ejecta of the nearby small ice moons. Because
427 silicate-rich grains of this size have not been detected in the E-ring, these must originate from a
428 different source, possibly the nearby moons Janus and Epimetheus or the F- and G-rings.

429
430 The Low Energy Magnetospheric Measurements System (LEMMS) of the MIMI energetic
431 charged particle detector made the first comprehensive survey of the planet's radiation belts inward
432 of Saturn's G-ring and monitored the environment of the five small moons. LEMMS measures
433 energetic electrons and ions from 18 and 27 keV respectively, and well into the MeV energy range.
434 The region inward of Saturn's G-ring has been sampled in the past on several occasions with
435 Pioneer 11 and *Cassini* (44-46). It contains the location where both proton and electron radiation
436 belts have their highest intensities, between the G-ring and Janus and Epimetheus's orbits. Inward
437 of that maximum intensities drop gradually up to the outer edge of Saturn's A-ring which absorbs
438 all energetic particles. Superimposed on the radial profile of radiation belt fluxes are localized
439 dropouts originating from Saturn's moons and rings (47). While several of these features can be
440 attributed to specific moons, like Janus and Epimetheus (48), any influences by Pandora,
441 Prometheus and Atlas (orbiting within the radiation belt boundaries) are less clear. These moons
442 orbit close to Saturn's A and F-rings and separating the different contributions was not possible
443 until now due to the low statistical significance of any past observations. Understanding how
444 effectively these moons sweep-out particle radiation is also important for describing the space
445 weathering environment to which their surfaces are exposed to.

446

447 Fig. 8A shows count-rates of >12 and >25 MeV protons as a function of L-shell (L), averaged
448 from all the Proximal Orbits. The L-shell is defined as the distance from Saturn that a field line
449 intersects the magnetic equator and is given in multiples of the planet's radius (1 Rs = 60268 km).
450 The L-shell here describes the equatorial footpoint of Cassini's trajectory mapped along Saturn's
451 magnetic field, normalized to one planetary radius of 60268 km. A third-order multipole model
452 for Saturn's internal magnetic field was used to derive its value (47). The plot shows the well-
453 established sectorization of the MeV proton radiation belts, due to the moons and rings that absorb
454 any protons diffusing across their orbits (50,51). Among these different sectors, the least
455 characterized is the one we mark here as the "Minor Belt", centered at approximately L=2.29 and
456 sampled only twice before the Proximal Orbits. The belt gap outward of the Minor Belt is centered
457 near the F-ring (L~2.32) and the increased sampling of that region has verified that those gap's
458 boundaries coincide with the L-shells of Prometheus and Pandora (Fig. 8A - inset). Pandora and
459 Prometheus are therefore absorbing protons at a rate that is strong enough to counter the diffusive
460 influx of protons from the surrounding belt sectors. Effectively, the two moons and the F-ring form
461 an extended obstacle to proton radiation. The net result is that the weathering of Pandora's and
462 Prometheus's surfaces by energetic protons is negligible since they orbit within the proton
463 radiation gaps they create. Atlas's effects could not be distinguished from those of the A-ring, but
464 that moon is also exposed to very low proton fluxes. Overall, it is now established that almost all
465 of Saturn's inner moons (except Dione, Rhea or minor moons like Anthe or Pallene) orbit in
466 energetic ion free environments (52-54), a striking difference from that of the Jovian satellites
467 whose surface chemistry and exospheric properties are strongly affected by irradiation from high
468 fluxes of keV and MeV protons, oxygen and sulfur (55,56).
469



471 Fig. 8A. **Proximal orbit averaged count-rates of MIMI/LEMMS proton channels P7 and P8**
472 **(above 12 and 25 MeV respectively) as a function of L-shell, together with the 1- σ error bars.**

473 Absence of error bars indicates an error larger than the corresponding mean value. The orbits of
474 several of Saturn's large icy moons are also marked. The inset zooms into the region of the Minor
475 Belt, highlighting the absorbing effects of Atlas, Pandora, Prometheus and the A- and F-rings. Fig.

476 **8B. Proximal Orbit averaged count-rates of MIMI/LEMMS electron channel E5 (>800 keV)**
477 **as a function of L-shell.** Overplotted are the 1- σ error bars at each L-shell bin. The locations of
478 various moons and rings are also marked, as in Panel A. The inset shows time series of high time
479 resolution observations (1 sample per 0.3125 sec) from LEMMS channel E4, which has a similar
480 response to E5. The data were obtained from the second proximal orbit, on May 2, 2017. A blue
481 arrow marks an electron microsignature within one of the MeV electron "spikes" seen consistently
482 during *Cassini*'s outbound crossings near the L-shell of the A-ring's outer edge.

483
484 Fig. 8B shows Proximal Orbit averages of electron count-rates from LEMMS channel E5 (>0.8
485 MeV) as a function of L-shell. Electron radiation levels are more variable than those of protons,
486 as the sizeable error bars indicate, since moons and rings are not effective in sweeping out electrons
487 from their orbits (47,52,57). Inside L=2.4 (inwards of the Janus and Epimetheus orbits) electron
488 rates start to experience a shallow drop towards the outer edge of the A-ring (L=2.27). This drop
489 is interrupted by an unexpected enhancement of the mean electron rates, near the L-shells of the
490 F-ring, Pandora and Prometheus. The statistical 1- σ error bars in that location span more than two
491 orders of magnitude in amplitude, indicating also much higher variability than in the surrounding
492 regions. A survey of electron measurements from each Proximal Orbit reveals that this large scatter
493 is attributed to spiky enhancements of MeV electron fluxes observed in all the outbound crossings

494 outwards of the A-ring's edge and between $L=2.31$ and $L=2.35$. The radial extent of an individual
495 spike is less than 1800 km along the equatorial plane, and the electron intensity within them can
496 be enhanced by as much as a factor of 300 compared their surroundings. The inset of Fig. 8B
497 shows one such resolved spike, captured by the high time resolution measurements of LEMMS
498 Priority channel E4 (0.8-4.2 MeV) on May 2, 2017. Since measurements in the inbound portion of
499 *Cassini*'s orbit showed no evidence of similar spikes in the same L-shell range, we deduce that
500 these features are fixed around local noon, and their longitudinal extent ranges between 22° and
501 37° starting from a magnetospheric local time of 14:50 and in the clockwise direction. The
502 longitudinal extend cannot be constrained in the anticlockwise direction. Most of these
503 enhancements were seen around the L-shells of the F-ring, Prometheus and Pandora. This
504 unexpected electron belt component is therefore limited in local-time range. As a result, energetic
505 electron bombardment of the three moons is variable in intensity, episodic and will occur only for
506 a fraction of their orbit around Saturn. Material interaction signatures of energetic electrons are
507 seen as localized depletions (microsignatures) within the electron spikes. These may have come
508 from Atlas, Prometheus, Pandora or F-ring clumps (58); an example is shown with a blue arrow
509 in the Inset of Fig. 8B and could have formed only after the electron enhancement developed. The
510 age of such microsignatures can therefore set limits to the lifetime of these transient electron
511 structures and inform theories of their formation.

512

513 Finally, a first survey of the LEMMS measurements from times that *Cassini* was magnetically
514 connected to Saturn's main rings shows no discernible signal of trapped electron or proton
515 radiation above the detection limit of the instrument at the orbits of the Keeler and Encke gaps,
516 where Daphnis and Pan are orbiting.

517

518 **Summary and Conclusions**

519 The low densities of the small moons of Saturn, which were refined by these close flybys, are
520 consistent with accretion from ring material. The new data on the moons embedded in the A-ring
521 show that the color of these moons becomes more similar to the rings the closer they are to Saturn.
522 This result suggests there is an ongoing accretion of a reddish chromophore that may be a mixture
523 of organics and iron, onto the surfaces of the moons. The difference in color between the moons
524 and their adjacent ring may be explained by the accretion of bright, icy particles or, more likely,
525 water vapor from the E-ring. In essence each moon's surface is subjected to a balance between
526 these two ongoing processes, with their distance from Saturn and Enceladus determining the final
527 result, as illustrated in Fig. 4F. The detection of abundant ice grains by CDA supports this view.
528 The bluer core of Atlas is also explained by the accretion of E-ring particles, which have a wider
529 range of inclinations than main ring particles. If the ring moons are made out of the same material
530 as the rings, they would of course have been the same color, and the color gradient may come
531 *solely* from contamination by the E-ring.

532 The finding by MIMI of a dearth of high-energy ions also lessens the competing alteration
533 processes caused by the bombardment of magnetospheric particles. The strong crystalline water
534 ice band at 1.65 μm also suggests the lack of importance of these processes. This "low energy"
535 environment also renders comparisons with the identity of the red chromophore on the trailing
536 hemispheres of main moons of Saturn, especially Dione and Rhea, problematical, as they dwell in
537 a region where alterations by ions is significant and would tend to darken and redden the surfaces
538 (57). Finally, the possible contamination of Saturn's rings by bright icy particles or water vapor
539 qualifies the argument that the observed brightness of the rings bespeaks a recent formation (58).

540 The moons record a complex geologic history with groove formation caused by tidal stresses and
541 accretion of ring particles. The CDA finding of a porous surface further supports substantial
542 accretion. Although the topography and surface slopes strongly suggest the equatorial ridges of
543 Pan and Atlas are accreted from the rings and are not formed by normal surface transport, the
544 variety of forms of ridges on these objects, and the minimal ridges on Daphnis, show that much
545 remains to be understood about their formation and relation to the main rings. The high resolution
546 images strongly suggest exposures of a solid substrate distinct from the mobile regolith that
547 frequently covers essentially all of many small Solar System objects. These exposures may
548 eventually help reveal systematic trends of both solid body history and structures for the whole of
549 the Saturn satellite system.

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556

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741

742 **Table 1: Summary of five “best ever” flybys of Saturn’s ring moons during the Ring-**
743 **grazing Orbits**

744

Moon	Semi-major axis (R_s)	Rotation rate (days)	Date of flyby	Closest approach (km)	Spatial resolution improvement factor	Best resolution (Imaging; m/pixel)
Pan	2.22	0.575	7 March 2017	22,247	2	147
Daphnis	2.26	0.594	16 Jan 2017	22,336	>10	170
Atlas	2.29	0.602	12 April 2017	10,848	2	76
Pandora	2.35	0.629	18 Dec 2016	22,157	~3	132

Epimetheus	2.51	0.695	30 Jan 2017	3,625	6	36
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745

746

747 **Table 2: Sizes and mean densities of Saturn’s ring moons described in this paper and Janus**

748

Object	a, km	b, km	c, km	R _m , km	Density, kgm ⁻³	Gravity, cms ⁻²
Pan	17.3±0.2	14.1±0.2	10.5±0.7	13.7±0.3	400±32	0.2-1.7
Daphnis	4.9±0.3	4.2±0.8	2.8±0.6	3.9±0.5	274±142	0.0-0.4
Atlas	20.4±0.1	17.7±0.2	9.3±0.3	14.9±0.2	412±19	0.0-1.7
Pandora	51.5±0.3	39.5±0.3	31.5±0.2	40.0±0.3	509±12	2.0-5.9
Epimetheus	64.8±0.4	58.1±0.8	53.5±0.4	58.6±0.5	625±16	6.6-10.9
Janus	101.8±0.9	93.0±0.3	74.5±0.3	89.0±0.5	642±10	642±10

749

750 Semi-axes are of ellipsoids fit to shape models and rescaled to volume of the model. R_m, the mean
751 radius, is the radius of a sphere of equivalent volume.752 Masses for Atlas, Pandora and Epimetheus are from (25). Masses of Pan and Daphnis are from (26). For
753 a full table of Saturn’s small inner moons see (supplementary materials).754 **Supplementary Materials**

755 Overview of the Ring and Moon System of Saturn

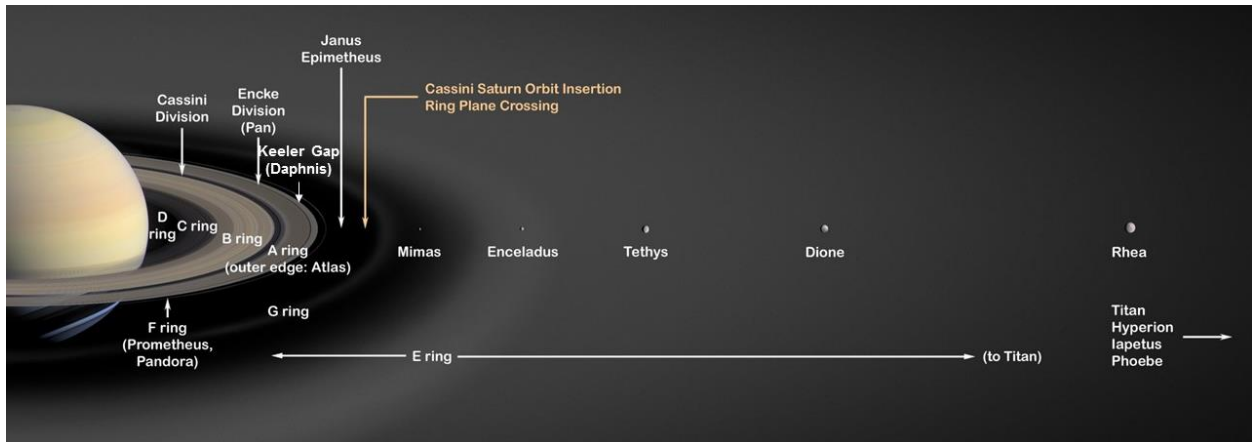
756 Complete Table of Densities

757 Methods: Visible Infrared Mapping Spectrometer

758 Methods: CIRS

759 Methods:CDA

760 **Overview of the Ring and Moon System of Saturn**761 Saturn has 62 moons that group into several categories. Besides the five main inner moons (Mimas,
762 Enceladus, Tethys, Dione, and Rhea), Hyperion, Titan, and Iapetus, the outer irregular moons, which
763 include Phoebe, the planet has a family of ring moons that orbit in gaps within Saturn’s rings (Pan in the
764 Encke gap and Daphnis in the Keeler gap) or skirt the outer edge of the A-ring (Atlas) and the F-ring
765 (Prometheus and Pandora). The coorbital moons Janus and Epimetheus, which exchange an orbit
766 outside the A-ring approximately every four years, are often classified as ring moons as well. Figure 1S
767 illustrates the position of the ring moons within Saturn’s ring system.



768

769 Figure 1S. A diagram showing the location of the main ring system of Saturn, the main inner moons, and
 770 the ring moons Pan, Daphnis, Atlas, Pandora, and Prometheus. The coorbital moons Janus and
 771 Epimetheus are often regarded as ring moons as well. Based on NASA PIA

772 **Table S1: Sizes and mean densities of small Saturnian satellites**

773

774 Object	a, km	b, km	c, km	Rm, km	density, kgm ⁻³	gravity, cms ⁻²
775 Pan	17.3±0.2	14.1±0.2	10.5±0.7	13.7±0.3	400± 32	0.2- 1.7
776 Daphnis	4.9±0.3	4.2±0.8	2.8±0.6	3.9±0.5	274± 142	0.0- 0.4
777 Atlas	20.4±0.1	17.7±0.2	9.3±0.3	14.9±0.2	412± 19	0.0- 1.7
778 Prometheus	68.5±0.5	40.5±1.4	28.1±0.4	42.8±0.7	460± 21	0.8- 5.8
779 Pandora	51.5±0.3	39.5±0.3	31.5±0.2	40.0±0.3	509± 12	2.0- 5.9
780 Epimetheus	64.8±0.4	58.1±0.8	53.5±0.4	58.6±0.5	625± 16	6.6- 10.9
781 Janus	101.8±0.9	93.0±0.3	74.5±0.3	89.0±0.5	642± 10	10.9- 16.9
782 Aegaeon	0.7±0.0	0.3±0.1	0.2±0.0	0.3±0.0	539± 140	0.001-0.005
783 Methone	1.9±0.0	1.3±0.0	1.2±0.0	1.4±0.0	307± 30	0.1- 0.1
784 Pallene	2.9±0.4	2.1±0.3	1.8±0.3	2.2±0.3	251± 75	0.1- 0.2
785 Telesto	16.6±0.3	11.7±0.3	9.6±0.2	12.3±0.3		
786 Calypso	14.7±0.3	9.3±0.9	6.4±0.3	9.5±0.4		
787 Polydeuces	1.5±0.3	1.3±0.4	1.0±0.2	1.3±0.3		
788 Helene	22.6±0.2	19.6±0.3	13.3±0.2	18.1±0.2		

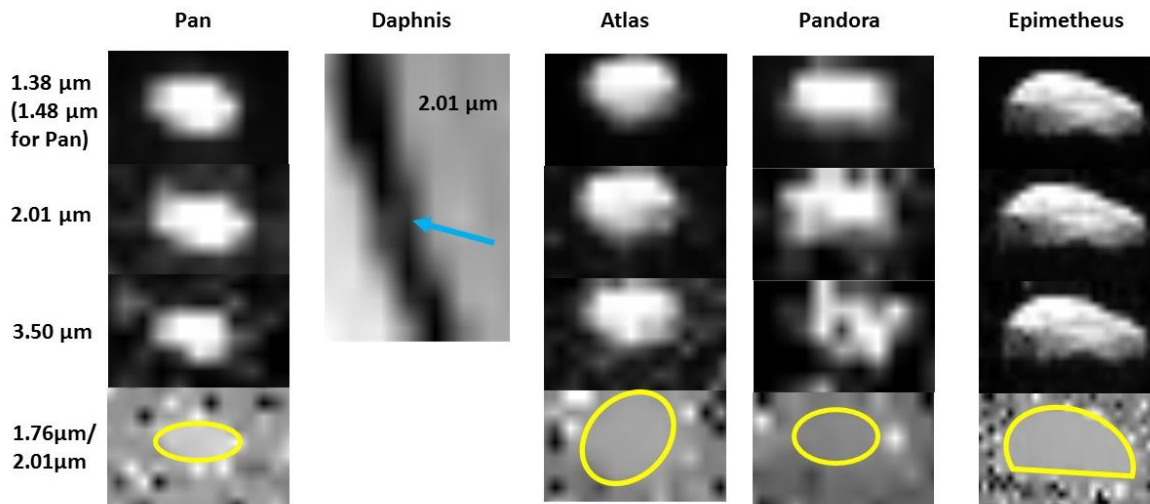
789 Semi-axes are of ellipsoids fit to shape models and rescaled to volume of the model. Rm, mean radius, is
 790 the radius of a sphere of equivalent volume.

791 Masses for Janus, Epimetheus, Atlas, Prometheus, and Pandora are from (25). Masses of Pan and
 792 Daphnis from (26). Masses of Aegaeon, Pallene, Methone are estimates from equilibrium shape
 793 interpretations (6). Masses of Telesto, Calypso, Polydeuces and Helene are unknown.

794 **Methods: Visible Infrared Mapping Spectrometer Observations**

795 The wavelength range of VIMS, from 0.35 μm to 5.1 μm , covers 99% of the reflected solar spectrum in
 796 352 spectral channels, with spatial resolution of 0.5 mradian and spectral resolution ranging from 1.46
 797 nm in the visible region (0.35-1.05 μm) to 16.6 nm in the NIR (0.85-5.1 μm). These are key spectral
 798 ranges for identifying volatiles including water ice, organics, and minerals. VIMS was also capable of a
 799 high-resolution spatial mode offering double resolution in one dimension. The instrument had separate
 800 visible and infrared channels, with visible light captured by a 512X512 CCD detector and IR photons
 801 captured on a 1X256 InSb detector.

802 Fig. 4 shows the best images for the five moons at 1.38 (1.48 for Pan), 2.01, and 3.50 μm (only 2.01 is
 803 shown for Daphnis, due to the low spatial resolution of the images; a positive identification was made by
 804 coaligning the VIMS and ISS images). A ratio image of 1.76/2.01 μm , representing the spectral
 805 continuum to the most prominent water ice band, is also shown. No spatial variations in the water icy
 806 band imply uniformity in abundance and texture on the individual moons. Due to its much higher
 807 spatial resolution, ISS is better suited to seeking visible color variations on the moons.



808
 809 **Fig. 2S. Infrared images of the five ring moons studied during the Ring-grazing Orbits at 1.38 (1.48 for**
 810 **Pan), 2.01 and 3.50 μm .** The bottom row is a ratio of the continuum at 1.76 μm to the water ice
 811 absorption band at 2.01 μm , showing uniformity on all the moons' surfaces (the images for Daphnis
 812 were too noisy to construct this ratio).

813 **Methods: The Cassini Infrared Spectrometer**

814 The detections of both Atlas and Epimetheus were made using dedicated CIRS scans bracketed by ISS
 815 observations. Epimetheus was detected on 30 Jan 2017 during a scan that occurred between 19:54:20
 816 to 20:05:50 UTC, at a distance that decreased from 80,179 to 67,237 km. During this time the sub-

817 spacecraft position changed from 345.0° W/73.5° N to 346.5° W/73.7° N, the local time at the sub-
818 spacecraft point increased from 271° to 276° and the phase increased slightly from 68.0° to 68.5°.

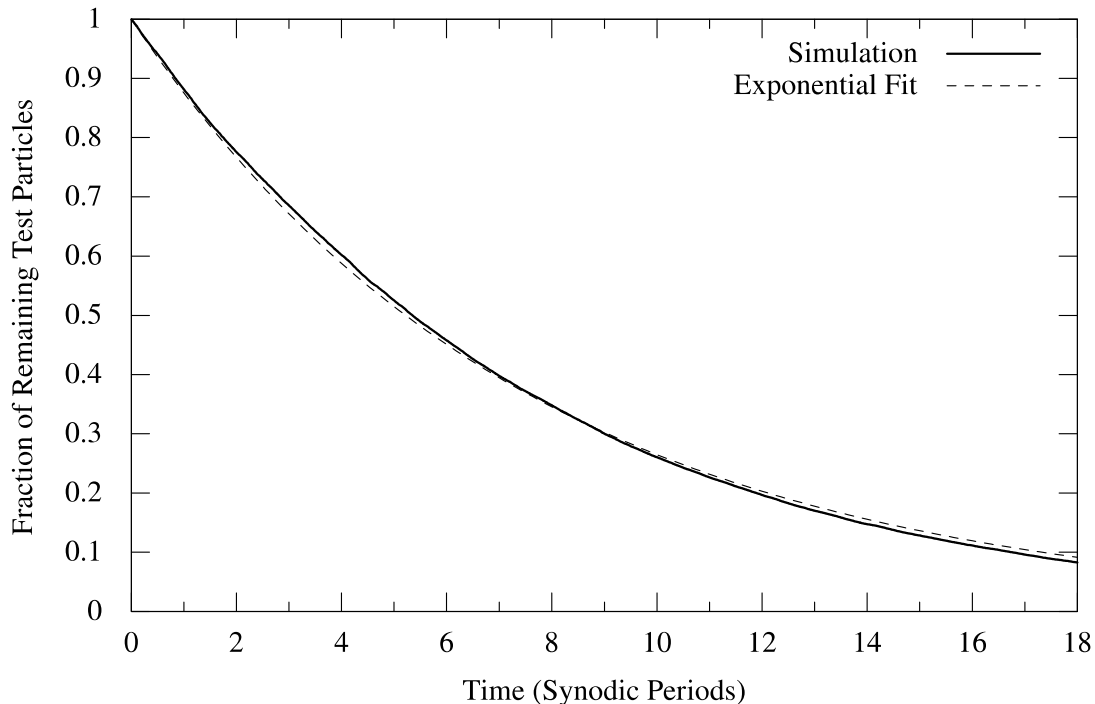
819 Atlas was detected a few months later, on 12 April 2017, during a scan that ran from 13:16:39 to
820 13:24:40 UTC, at a distance that decreased from 33,572 km to 24,580 km. During that time the phase at
821 the sub-spacecraft point decreased from 51.2° to 47.2°, the sub-spacecraft position changed from 141.9°
822 W/60.1° N to 149.8° W/52.1° N, and the local time at the sub-spacecraft point decreased from 226° to
823 221°.

824 In both detections CIRS used its focal plane 3 (FP3, which covers 570–1125 cm⁻¹) to scan the target and
825 background sky. The images have been rotated so they are also in RA/Dec coordinates. However, the
826 scale of the CIRS data and the ISS images is notably different, as indicated by the 10 km scale bar given
827 in Fig. 5 in the main text. Images of Atlas taken before and after the CIRS scan were ISS image
828 N00279648 using CL1 and CL2 filters on Apr. 12, 2017 at 1:15 UT; ISS image N00279649 taken using CL1
829 and CL2 filters on Apr. 12, 2017 1:27 UT. Images of Epimetheus taken before and after the CIRS scan
830 were ISS image N00275708 taken using CL1 and CL2 filters on Jan. 30, 2017 7:53 UT and ISS mage
831 N00275709 taken using CL1 and UV3 filters on Jan. 30, 2017 8:07 UT.

832 Numerical simulations and the lifetimes of the dust particles

833 We performed numerical simulations of dust particles in the Janus-Epimetheus ring to estimate their
834 lifetimes. In Fig. 1, the solid line shows the fraction of remaining particles (those which did not yet
835 collide with Janus, Epimetheus, Saturn or its dense rings). To obtain the mean lifetime τ of the dust
836 particles, we fit an exponential function $f(t) = \exp(-t/\tau)$ to the simulation results, shown as dashed
837 line, yielding $\tau = 60$ years.

838



839

840 Fig 3S. **Particle Lifetimes.** The solid line shows the evolution of the fraction of remaining particles (which
 841 did not collide with Janus, Epimetheus, Saturn or its dense rings), whereas the dashed line denotes an
 842 exponential fit to this evolution leading to a mean lifetime of $\tau = 60$ years. The synodic period of Janus
 843 and Epimetheus is about 8 years.

844

845 We assume the dust particles to be spheres with a radius of $s = 1.6 \mu\text{m}$, which is consistent with the
 846 size of particles measured to comprise the Janus-Epimetheus ring by the HRD detector of Cassini's CDA.
 847 In the simulations, we consider the gravity of Saturn (including its oblateness up to 6th order), the
 848 gravity of Janus and Epimetheus, as well as solar radiation pressure and the Lorentz force due to
 849 Saturn's magnetic field (considered as a dipole field). Table 1 summarizes the parameters used in the
 850 simulations.

851

852 We integrated the equations of motion of 40,000 particles for about 150 years. For simplicity, the initial
 853 eccentricities and inclinations of the dust particles were chosen to be Rayleigh distributed with mean
 854 values of $\langle e \rangle = 0.0068$ and $\langle i \rangle = 0.17$ deg, resembling a ring width of about 2000 km and a ring scale
 855 height of 350 km. The initial ephemeris data of the Sun, Janus, and Epimetheus were obtained from data
 856 provided by the NAIF SPICE toolkit using the kernel files de430.bsp, sat375.bsp, sat378.bsp, and
 857 cpck23Aug2007.tpc.

858 Table 1. Parameters used in the simulations: solar radiation pressure efficiency factor Q_{pr} , solar
 859 constant Q_s , electrostatic grain potential ϕ_{grain} , dipole term of Saturn's magnetic field g_{10} , and the
 860 gravitational harmonic coefficient J_2, J_4 , and J_6 .

Parameter	Value	Reference
<i>Radiation Pressure:</i>		
Q_{pr}	0.49	(Liu, 2016)
Q_s	$1.36 \times 10^3 \text{ Wm}^{-2}$	
<i>Lorentz Force:</i>		
ϕ_{grain}	-1.6 V	(Horanyi, 2009)
g_{10}	$2.1162 \times 10^{-5} \text{ T}$	(Burton, 2009)
<i>Saturn's Oblateness:</i>		
J_2	1.629071×10^{-2}	(Jacobson, 2006)
J_4	-9.3583×10^{-4}	(Jacobson, 2006)
J_6	8.614×10^{-5}	(Jacobson, 2006)

861

862 The lifetime of the particles in the Janus and Epimetheus ring is also restricted by the surrounding
 863 plasma, neglected in our simulations. The permanent bombardment of the dust particles by Saturn's
 864 plasma particles leads to a sputtering of their surface, which reduces the size of the particles. The typical
 865 plasma sputtering rate in the E ring is about $1 \mu\text{m}$ in 50 years (Jurac, 2001). However, the plasma density

866 is decreasing by two orders of magnitude towards Saturn (Elrod, 2014) which increases the sputtering
867 lifetime of a 1.6 μm sized particle to $\tau_{\text{sputt}} = 8000$ years.

868

869 Collisions with the plasma particles further accelerate the dust particles causing an outward drift
870 (plasma drag). While drift rates of 1000 km/yr are typical in the E ring for 1.6 μm sized grains (Horanyi,
871 2008), the drift rate in the Janus-Epimetheus region is only 10 km/yr due to the lower plasma densities
872 (Elrod, 2014). Therefore, a dust particle is estimated to leave the Janus-Epimetheus ring after about 210
873 years, assuming a HWHM of 2100 km.

874

875 Summarizing, the collisions with the moons are the dominating sink for the ring particles leading to a
876 typical lifetime of about 60 years, which provides a fair explanation of the impact-generated ring
877 embracing the orbits of Janus and Epimetheus.

878 **Impact-ejection model**

879 It is assumed that the dust in the Janus-Epimetheus ring is generated by the process of impact-ejection –
880 the ejection of secondary dust particles by impacts of fast micro-meteoroids onto atmosphereless
881 planetary satellites.

882

883 In order to estimate the dust densities in the ring, we apply the impact-ejection model (Krivov, 2003). In
884 this model, the total mass ejected from the target surface per unit time is given by

$$885 \quad M^+ = F_{\text{imp}} Y S, \quad (1)$$

886 where F_{imp} is the impactor mass flux (density) at the target and S is the target's cross sectional area
887 (Krivov, 2003). Y is the yield defined as the ratio of the total mass ejected by an impactor to its mass,
888 which strongly depends on the impact speed v_{imp} as well as the impactor mass m_{imp} and the
889 composition of the target surface. We use an empirical relation for the yield (Koschny, 2001), which
890 reads (in SI units)

$$891 \quad Y = 2.85 \times 10^{-8} (0.015)^{\frac{x}{100}} \rho_{\text{ice}} m_{\text{imp}}^{0.23} v_{\text{imp}}^{2.46}, \quad (2)$$

892 where $\rho_{\text{ice}} \approx 930 \text{ kg/m}^3$ is the mass density of ice at a temperature of 100 K.

893

894 The impactor flux is $2.7 \times 10^{-16} \text{ kg m}^{-2} \text{ s}^{-1} \leq F_{\text{imp}}^{\infty} \leq 3.3 \times 10^{-15} \text{ kg m}^{-2} \text{ s}^{-1}$ at the Hill radius of
895 Saturn and has been obtained together with the impactor size and speed distributions from *in situ*
896 measurements of the Cassini CDA (Kempf, 2018). The impactor flux and impact speeds are amplified due
897 to gravitational focusing by the planet (Colombo, 1966; Spahn, 2006). At the planetocentric distance of
898 Janus and Epimetheus ($2.5 R_s$), the mean focusing factors are ~ 4 for the impact speeds and ~ 25 for
899 the impactor flux, and the mean yield is $Y \sim 3800$, averaged over the impact speeds and impactor sizes,
900 respectively.

901

902 For the lower limit of the impactor flux, this gives a mass production rate of 0.64 kg/s for Janus and
903 0.27 kg/s for Epimetheus.

904

905 The cumulative size distribution of the debris is assumed to be a power law with exponent $-\alpha$, so that
906 the number of particles with radii larger than s ejected from the target surface per unit time is given by

907
$$N^+(\gt s) = \frac{3 - \alpha}{\alpha} \frac{M^+}{m_{\max}} \left(\frac{s_{\max}}{s} \right)^\alpha, \quad (3)$$

908 where m_{\max} (s_{\max}) is the maximal ejecta mass (size). The index α depends on the target material and
909 ranges from 1.5 for loose to 3 for solid targets (Krivov, 1998). *In situ* measurements give for the index of
910 the size distribution values of $\alpha \sim 2.4$ for the dust atmospheres around the Galilean moons (Krüger,
911 2003), and a value of $\alpha \sim 2.7$ for the lunar dust atmosphere (Horanyi, 2015). The largest ejecta is
912 typically similar in size to the largest impactor (Sachse, 2017).

913

914 For $\alpha = 2.4$ and $m_{\max} = 10^{-8}$ kg (an icy particle with $s_{\max} \approx 140 \mu\text{m}$), 6.9×10^{12} particles larger than
915 $1.6 \mu\text{m}$ from Janus and 2.9×10^{11} from Epimetheus are ejected.

916

917 Impact experiments and scaling laws (Housen, 2011) show that the differential speed distribution is
918 proportional to a power law with exponent $-\gamma - 1$

919
$$f(u) = \frac{\gamma}{u_{\min}^{-\gamma} - u_{\max}^{-\gamma}} u^{-\gamma-1} \Theta(u - u_{\min}) \Theta(u_{\max} - u), \quad (4)$$

920 where $\Theta(x)$ denotes the unit step function, which is one for $x \geq 0$ and zero otherwise. The index γ
921 depends on properties of the target material and ranges from $\gamma = 1$ for highly porous to $\gamma = 2$ for
922 nonporous materials (Krivov, 2003).

923

924 The minimal ejection speed u_{\min} is chosen so that the kinetic energy of the ejecta is a few (tens of)
925 percent of the kinetic energy of the impactor (Asada, 1985; Hartmann, 1985). Hard surfaces (e.g. ice) are
926 generally less dissipative than soft surfaces (e.g. snow, regolith). In case the ejecta sizes and ejection
927 speeds are uncorrelated, the relation between Y , γ , and u_{\min} reads (Krüger, 2000)

928
$$\frac{K_e}{K_{\text{imp}}} = Y \frac{\gamma}{2 - \gamma} \left(\frac{u_{\min}}{v_{\text{imp}}} \right)^2 \left[\left(\frac{u_{\min}}{u_{\max}} \right)^{\gamma-2} - 1 \right] \quad \text{for } \gamma \neq 2 \quad (5)$$

929 and

930
$$\frac{K_e}{K_{\text{imp}}} = 2Y \left(\frac{u_{\min}}{v_{\text{imp}}} \right)^2 \ln \left(\frac{u_{\max}}{u_{\min}} \right) \quad \text{for } \gamma = 2, \quad (6)$$

931 where the subscripts “imp” and “e” refer to impactor and ejecta related variables, respectively.

932

933 The maximal ejection speed is larger than the escape velocity of the largest satellites in the Solar System
934 ($u_{\max} > 3$ km/s). For example, impact-ejecta escape the gravity of the Galilean moons and form a dust
935 ring between their orbits (Krivov, 2002). Integrating Equation (4) for speeds larger than the escape
936 velocity, $u > v_{\text{esc}}$, gives the fraction of escaping ejecta.

937

938 Table 2S summarizes the parameters used for the impact-ejection model and the results.

Parameter	Value	Reference/Comment
F_{imp}^{∞}	$2.7 \times 10^{-16} \text{ kg m}^{-2} \text{ s}^{-1}$	(Kempf, 2018)
F_{imp}	$6.7 \times 10^{-15} \text{ kg m}^{-2} \text{ s}^{-1}$	
Y	3800	
M^+	0.9 kg s^{-1}	70% Janus and 30% Epimetheus
α	2.4	(Krüger, 2003)
m_{\max}	$1.0 \times 10^{-8} \text{ kg}$	(Krivov, 2003)
$N^+(\gt s)$	$9.8 \times 10^{11} \text{ s}^{-1}$	70% Janus and 30% Epimetheus
K_e/K_{imp}	0.05	
γ	1.0	(Krivov, 2003)
$N_{\text{esc}}^+(\gt s)$	$5.5 \times 10^{10} \text{ s}^{-1}$	60% Janus and 40% Epimetheus

939 Table 2. Parameters and results of the impact-ejection model.

940

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