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Energetic protons trapped between Saturn and its rings

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Cassini's Magnetosphere Imaging Instrument has obtained the first measurements of a radiation belt that resides just above Saturn's dense atmosphere and is permanently decoupled from the rest of the magnetosphere through a 62000-km wide particle absorbing corridor formed by the planet's A to C-

rings. This belt extends across Saturn's D-ring and comprises mostly $\sim 0.025 - >1$ GeV protons produced through Cosmic Ray Albedo Neutron Decay (CRAND). CRAND is balanced by proton losses to atmospheric neutrals and D-ring dust rather than by magnetospheric diffusion which affects the belts beyond the rings. Strong proton depletions mapping onto the D-ring's D68 and D73 ringlets contrast with the absence of notable proton losses along its D72 ringlet, and reveal a highly-structured and diverse dust environment configuration near Saturn.

1 Introduction

2 During the Proximal Orbit phase of the Cassini mission (23 April - 15 September 2017), the
3 spacecraft completed 22 crossings through the narrow gap between Saturn's upper atmosphere
4 and its rings (Figure 1) and performed the first in-situ measurements of the local energetic
5 charged particle environment with the Magnetosphere Imaging Instrument, MIMI (1).

6 Observational evidence that trapped particle radiation may be confined inward of Saturn's
7 rings was first obtained during Cassini's Saturn Orbit Insertion (SOI, 1 July 2004) through En-
8 ergetic Neutral Atom (ENA) imaging of this region by MIMI (2). These observations revealed
9 an emission of 20 to 50 keV/nucleon ENAs coming from a low-altitude, trapped ion popula-
10 tion of the same energy, which was subject to charge-exchange with neutral atoms of Saturn's
11 upper atmosphere. The ions that produced the low altitude ENA emission are thought to de-
12 rive from planetward ENAs generated in Saturn's middle magnetosphere (3, 4). Following their
13 re-ionization through charge-stripping reactions in the planet's upper atmosphere, the newly
14 converted ions get temporarily trapped by the planet's magnetic field, before charge exchange
15 converts them back into the ENAs that MIMI detected (2). The exact altitude of the ion popu-
16 lation driving this ENA emission is unknown but could be similar to that of the 0.06-1 MeV

17 ions that were recently detected between 4300 and 18000 km above Jupiter's 1-bar atmospheric
18 level and were possibly generated by the same mechanism (multiple charge-exchange) (5).

19 Higher energy protons, at MeV energies and above, can be supplied to the inner trapping
20 region through the Cosmic Ray Albedo Neutron Decay process (CRAND), as it was initially
21 pointed out by (6) and (7). CRAND protons are among the β -decay products of secondary
22 (albedo) neutrons which form after Galactic Cosmic Rays (GCRs) impact Saturn's atmosphere
23 and/or its dense rings. Because neutrons are not bound by the planetary magnetic field, they
24 can fly away from their generation site and through the trapping region, within which they may
25 release their β -decay proton. CRAND is a key process sustaining the proton radiation belts of
26 Earth and those of Saturn outside its rings ("main radiation belts") (8–12).

27 While CRAND undoubtedly generates energetic protons near the planet, it was not clear
28 before Cassini's Proximal orbits whether these protons could accumulate in large numbers and
29 form a localized radiation belt. Quantitative models that were used to predict upper limits of
30 the proton intensities in this region (13) relied on a series of input parameter extrapolations and
31 simplifying assumptions for the determination of the CRAND source rate and the loss rates
32 of protons to atmospheric neutrals and to ring dust. In particular, it was not known if there
33 would be a significant signal from energetic protons across the D-ring ($\sim 1.11 - 1.24 R_S$) (14)
34 and its three ringlets, named as D68, D72 and D73 and centered at 1.12, 1.19 and 1.22 R_S ,
35 respectively (15, 16), all of which are contained within the trapping region. The input values for
36 the description of the D-ring properties were so poorly constrained that even the most realistic
37 predictions for the 10-60 MeV proton fluxes spread over two orders of magnitude, with the
38 lowest values near MIMI's detection limits.

39 The simulations indicated that the dynamics of MeV protons in this inner radiation belt
40 would be determined by physical processes different from those affecting protons of the main
41 radiation belts. Proton intensities in Saturn's main radiation belts are limited by radial diffusion,

42 which controls how fast these particles are distributed within the orbits of the planet's large icy
43 moons, where they get subsequently absorbed (12, 17). Similarly, radial diffusion near the planet
44 could act as a proton sink by gradually moving protons to the massive C-ring (1.24 - 1.53 R_S)
45 and the dense atmosphere ($\lesssim 1.02 R_S$). Since, however, radial diffusion rates near the planet
46 were projected to be extremely low (17, 18), it was instead proposed that the intensity of the
47 proton fluxes would be primarily determined by a balance of the CRAND source rate against
48 losses of protons to dust and neutral gas. Losses to the equatorially confined dust, in particular,
49 can be transmitted along the magnetic field lines sampled by Cassini's high-inclination Proximal
50 orbit trajectory, allowing MIMI to obtain radial dust density scans of the D-ring system from a
51 large distance (e.g. Figure 1, red lines), a capability not available to other in-situ instruments of
52 Cassini (e.g. (19)).

53 Probing the local dust and gas environment and the CRAND source is further simplified
54 because proton populations of the inner trapping region are permanently isolated from the rest
55 of the magnetosphere. Saturn's dense A to C-rings form a ≈ 62000 -km wide particle ab-
56 sorbing corridor (1.24-2.27 R_S) that is impermeable for any magnetospheric particle that gets
57 transported inward of 2.27 R_S . Mixing of energetic particle populations near the planet from
58 different source locations (10), which may occur at Earth and Jupiter and complicate the in-
59 terpretation of relevant measurements, is inhibited at Saturn. This filtering is also important
60 for unambiguously detecting CRAND electrons, the other β -decay product of albedo neutrons,
61 the presence of which was only recently resolved at the Earth (20). Furthermore, the strong
62 magnetic field near Saturn forms a very stable energetic charged particle trapping environment
63 that is unresponsive to solar wind or magnetospheric transients that affect the magnetosphere at
64 larger distances. Finally, the location of the inner trapping region establishes a constant source
65 rate for CRAND protons and electrons, since the primary GCR energies that drive CRAND
66 and define its source strength, exceed 20 GeV (21). GCRs above this energy show no sign of

67 heliospheric modulation (22). The stability of the CRAND source rate, in particular, has proven
68 useful to unambiguously decompose the contribution of different magnetospheric processes that
69 control the evolution of Saturn’s main radiation belts (12).

70 In the following sections we present MIMI’s ground-truth measurements of trapped protons,
71 ions and electrons in Saturn’s innermost trapping region and we discuss the findings in the
72 context of the theory, simulations and past observations discussed above.

73 **Instrumentation and methodology**

74 **Magnetosphere Imaging Instrument (MIMI):** The MIMI instrument (1) comprises three
75 different sensors, the Low Energy Magnetospheric Measurement System (LEMMS), the Charge-
76 Energy Mass Spectrometer (CHEMS), and the Ion Neutral Camera (INCA).

77 Here we rely mostly on LEMMS, which is a double-ended, charged particle telescope that
78 based on the latest calibration (23) can measure the energy and angular distribution of 27 keV
79 to >300 MeV protons and of 18 keV to ~ 10 MeV electrons. Certain LEMMS channels can
80 also distinguish heavier MeV ions from protons but lack mass resolution (24). CHEMS has
81 three particle telescopes which measure the energy, mass, and charge state of energetic ions
82 between 3 and 220 keV/e. INCA obtains Energetic Neutral Atom (ENA) images in oxygen and
83 hydrogen, as well as high sensitivity ion spectra in the energy range from 7 keV/nucleon to 8
84 MeV/nucleon.

85 **Methods:** The majority of the results presented here are based on observations by LEMMS
86 channels P8 (>25 MeV H^+) and E7 (>300 MeV H^+ and >7 MeV e^-). These two channels
87 achieve the most efficient rejection of instrument penetrating protons that can contaminate the
88 measurements. We occasionally cite channel P9 (>60 MeV H^+ and >1 MeV e^-), due to its
89 high-sensitivity, omnidirectional proton response. Unless otherwise stated, we will quote chan-

90 nels P8, E7 and P9 by referring to their proton energy response, since the respective measure-
91 ments are dominated by protons, as we later explain. Designations of other LEMMS electron
92 or ion channels will be given when relevant observations are shown.

93 Differential proton flux spectra were obtained through a forward model that reconstructs
94 the >25 MeV and >300 MeV count rates by convolving those channels angular and energy
95 response functions with predefined shapes of proton energy spectra and angular distributions
96 (23) (Figures S.2, S.5). For lower proton energies or non-proton species, LEMMS, CHEMS
97 and INCA could only provide upper flux limits. The determination of the upper limits is also
98 detailed in (23) (Figure S.7).

99 In order to magnetically map the in-situ measurements by MIMI, we calculated the L-shell,
100 the equatorial pitch angle and the loss-cone through an empirical third-order magnetic field
101 model (25). We define the L-shell (L) as Cassini's field line distance from Saturn's rotation axis
102 along the magnetic equator, normalized to a planetary radius. The equatorial pitch angle (α_{eq}) is
103 the angle between the proton velocity and the magnetic field at the magnetic equator, while the
104 loss-cone corresponds to the pitch angle below which the mirror altitude of the trapped particles
105 is lower than 1000 km, well into the dense atmosphere.

106 **Innermost energetic particle trapping region observations**

107 **Raw proton data:** The raw count rates of >25 MeV, >300 MeV and >60 MeV protons
108 are plotted in Figure 2 as a function of L , from all the times that Cassini was magnetically
109 connected to regions inwards of Saturn's C-ring. We can identify several major features in this
110 L-shell profile even before we convert these raw count rates to physical units.

111 We find a strong signal on magnetic field lines that thread through the D-ring, even though
112 trapped energetic protons at those L-shells bounce through that ring every few seconds and
113 could sustain heavy losses. The effects of proton absorption from two of the D-ring's ringlets

114 are more severe. The count rate dropout that develops at the outer boundary of the trapping
115 region maps to the location of the D73 ringlet (which extends over $0.02 R_S$) instead of the C-
116 ring and makes the radiation belt slightly narrower than initially expected, since the presence
117 of the ringlets was not taken into account in past simulations (13). A second major count rate
118 dropout, which splits the inner radiation belt in two main segments, is seen at the L-shell of the
119 D68 ringlet. No obvious absorption signature is observed in association with the D72 ringlet.

120 In agreement with model predictions (13), the dense upper atmosphere limits the intensi-
121 ties of trapped radiation towards the lowest L-shells. The high sensitivity, omnidirectional >60
122 MeV proton measurements (Figure 2C) registered counts at levels above the instrumental back-
123 ground down to $L \sim 1.03$, indicating that some minimal flux of MeV protons may survive down
124 to at least 1800 km above the 1-bar atmospheric pressure level.

125 **Proton pitch angle distributions:** The large scatter of the MeV proton rates observed at
126 any given L-shell (Figure 2), can be attributed to changes in both the spacecraft's latitude and
127 LEMMS's equatorial pitch angle pointing, α_{eq} (Figure S1, (23)). A successful reconstruction
128 of these two dominant dependencies (Figure S.4 (23)), requires the actual proton pitch angle
129 distribution (PAD) is much steeper than what is observed with the coarse angular resolution
130 of LEMMS. If we describe the PAD as $\propto \sin^N \alpha_{eq}$ outside the loss cone, we obtain that the
131 power, N , ranges between 10 (at the D-ring) and 100 (near the atmosphere). For reference, this
132 exponent is lower than ~ 6 in Saturn's main proton radiation belts (26–28).

133 Any residual signal not reproduced by the aforementioned reconstruction indicates that tem-
134 poral variations, if present, may only account for changes comparable to or smaller than the 1σ
135 statistical uncertainty in the LEMMS signal.

136 **Proton energy spectra (≥ 25 MeV):** Differential proton intensities were evaluated assuming
137 a spectral form that is a simple power law in energy and has a cutoff at 20 GeV. Even if Saturn's

138 magnetic field can stably trap even higher energies (29), the proton gyroradius above 20 GeV
139 becomes comparable to the width of the trapping region (30). The resulting spectrum at L=1.1,
140 where the proton intensities peak, is plotted in Figure 3A.

141 We find that the proton spectrum is hard (meaning that flux decreases slowly with increasing
142 energy), with a spectral index of ~ -1 . For such a spectrum, relativistic protons (>0.938 GeV)
143 could make up a considerable contribution to the count rate of the >300 MeV channel. The
144 fact that the >300 MeV proton channel recorded counts even when LEMMS was pointing well
145 into the atmospheric loss cone (Figure 2A,B, S1.A), is an indirect but independent verification
146 that relativistic protons contribute to the measurements: such counts may only come from >0.9
147 GeV instrument penetrating protons (Figure S.3, (23)).

148 The shape of the proton spectrum may be more complex than the power law we assumed.
149 For example, an additional spectral break could exist at ~ 100 MeV, where the efficiency of
150 CRAND neutron production changes (9, 31). Such a spectral shape cannot be unambiguously
151 constrained with just the two proton channels used here. Still, even if we pre-define its shape,
152 the spectrum at >100 MeV remains hard, indicating that it may be possible to constrain the
153 proton fluxes at the GeV range.

154 **L-shell distribution of protons:** The L-shell dependence of the differential proton fluxes at
155 300 MeV, deconvolved from their latitudinal and pitch angle dependencies, (Figure 4A) shows
156 that the innermost proton belt peaks around L=1.1, just inward of the inner D-ring edge and in
157 agreement with model predictions (13). That is a region where the combined material density
158 from the D-ring dust and the atmospheric neutrals reaches a minimum, allowing the proton
159 intensities to achieve the highest intensity levels.

160 The depth of the dropout attributed to the D68 ringlet has a clear pitch angle dependence.
161 With decreasing α_{eq} , the depth of the absorption becomes less pronounced, as expected for

162 charged particles mirroring at high-latitudes, well away from where proton losses to dust occur.
163 No absorption signature is resolved at the location of the D72 ringlet, even after the raw counts
164 are processed and deconvolved of their latitudinal and pitch angle dependencies.

165 **Low altitude ENA emissions and upper limits of <25 MeV proton, ion and electron fluxes:**

166 Upper limits for <25 MeV protons, 18-832 keV electrons and >5 MeV/nuc helium and oxygen
167 are also included in Figures 3A,B. The results apply to L=1.1 but are similar within factors of
168 three to all the L-shell range of the inner trapping region. The upper limits indicate a drop of the
169 proton fluxes below about 25 MeV and negligible intensities for light or heavy ions. Evidence
170 for the absence, or at least the lack of significant electron fluxes at any energy that LEMMS
171 responds to (18 keV to ~10 MeV) is provided in (23) (Figures S.4, S.5). In essence, the only
172 resolvable trapped particle population with in-situ data comes from >25 MeV protons.

173 Even though MIMI did not observe keV protons in-situ, it detected remotely a 24-55 keV
174 proton ENA emission from Saturn during its periapsis crossing on day 148/2017 (Figure 5). The
175 proton population responsible for this emission must have resided below the lowest altitude of
176 ~3800 km sampled in-situ by MIMI on that day. The clear non-detection of ENAs in several
177 other cases that INCA had the correct pointing to observe them (e.g. day 247/2017) suggests
178 that the protons creating the ENA emission are transient.

179 **Discussion**

180 **Origin of MeV protons from ring CRAND:** Several lines of evidence verify that CRAND is
181 the primary source process of the >25 MeV proton belt: the presence of protons, the extension
182 of the spectrum well above 300 MeV, the lack of any resolvable signal from heavy ions and the
183 temporal stability and the L-shell profile of the proton intensities. The L-shell profile (Figure 4)
184 agrees qualitatively well with that derived from simulations (13), for which a CRAND source

185 was used as an input. Since this inner radiation belt is permanently decoupled from the rest
186 of the magnetosphere, its detection alone constitutes one of the most direct observations of the
187 CRAND process operating in our solar system.

188 In case of Saturn, CRAND may not only be catalyzed through the planet's atmosphere but
189 also through the rings, from where we argue that the majority of CRAND protons that populate
190 the inner radiation belt originate. One reason is that the rings have a significantly higher neutron
191 yield than the planet's atmosphere (31). In addition, atmospheric neutrons that can reach the
192 inner trapping region may only come off a latitude range below 36° , which is accessible to
193 >40 GeV GCRs (21). Such GCRs have about four times lower integral flux than the >20 GeV
194 GCRs which reach the main rings, that also offer a 50% larger neutron production area than the
195 limited atmospheric zone. The attribution of the inner radiation belt source to ring CRAND is
196 important for separating atmospheric and ring CRAND in the proton spectra of Saturn's main
197 radiation belts, which has not been possible until now (12, 17).

198 **Radiation belt and atmosphere coupling:** The steep PAD inferred for both >25 MeV and
199 >300 MeV protons inward of the D-ring ($L \lesssim 1.1$) can be attributed to energy losses of these pro-
200 tons to Saturn's extended atmosphere. We demonstrate this in Figure 4 by plotting the inverse
201 value of the average atmospheric density encountered by protons of different pitch angles, as
202 they move along the magnetic field (bounce-averaged atmospheric density), against the fluxes
203 of 300 MeV protons. The inverse density profiles track the drop of the proton fluxes towards
204 the planet, mostly for $L \lesssim 1.1$. In a similar way, the terrestrial atmosphere is responsible for very
205 steep proton PADs in Earth's radiation belts (32, 33).

206 **Radiation belt and D-ring coupling:** For $L \gtrsim 1.1$, the inverse atmospheric density curves
207 deviate from the deduced 300 MeV proton flux profiles, suggesting that the losses to the D-ring
208 develop faster there. Using the D-ring density to proton flux scaling derived in (13), we estimate

209 that the D-ring column density needs to be below 10^{-8} g/cm² (13), which is orders of magnitude
210 lower than the corresponding A and B-ring values (10-500 g/cm², (34, 35)). The partial, dust-
211 driven depletion of the proton fluxes that we observe resembles the MeV proton interaction seen
212 at Saturn's G-ring (L=2.71) (17, 36, 37). Because losses to D-ring dust are more significant for
213 equatorially mirroring particles ($\alpha_{eq} \sim 90^\circ$), they are likely responsible the reduced pitch angle
214 anisotropy of protons compared (N~10) to the one observed at $L \lesssim 1.1$ (N~100).

215 Despite that, the anisotropy at $L \gtrsim 1.1$ remains large. The only remaining source of proton
216 anisotropy may come from the CRAND process: since CRAND protons get injected along the
217 direction of their parent, β -decay neutrons, their PAD may retain information about a prefer-
218 ential emission direction of neutrons from the rings. Simulations show that an isotropic, ring
219 neutron emission would result to similarly isotropic proton PADs near the planet (18). The steep
220 proton PAD at $L \gtrsim 1.1$ may then be evidence that the neutron injection from the rings is highly
221 anisotropic. Such an anisotropy may hold clues about the dust size distribution in Saturn's A-C
222 rings, as it has been previously suggested (9, 31).

223 **Diversity of the D-ring ringlets:** Only two out of the three ringlets of the D-ring were shown
224 to unambiguously influence the L-shell profile of the proton intensities (D68 and D73). D73
225 has a normal optical depth of $\sim 10^{-3}$ (38), which can be sufficient for depleting the energetic
226 protons that LEMMS detects (39). D68 causes a strong reduction of proton fluxes (Figures 2,
227 4), while D72, which is as bright as D68, appears to have no impact on the trapped protons.
228 This set of observations provides new insights on the diversity of the ringlets. The different
229 influences of D68 and D72 on protons suggest that the former ringlet concentrates significant
230 column mass in large grains and/or in its longitudinally confined arc, which has been observed
231 remotely (38).

232 **Comparison with Earth's radiation belts:** Figure 3A shows the >25 MeV proton spectra
233 from Saturn's inner trapping zone against those from $L=1.4$ in Earth's magnetosphere, where
234 the proton belt fluxes above 100 MeV peak (40). The comparison indicates that Earth fluxes are
235 about an order of magnitude higher for energies below 400 MeV. This difference is mostly due
236 to solar protons, which can reach low L-shells at Earth through radial transport, a source not
237 available at Saturn. A turnover occurs beyond ~ 400 MeV and into the GeV range, where the
238 projected proton fluxes at Saturn become stronger. Even though both Earth and Saturn produce
239 CRAND protons in the GeV range, the 600 times stronger magnetic moment at Saturn allows
240 a much more stable trapping of protons at relativistic energies (29). At Earth, trapped protons
241 have been observed up to at least 2.2 GeV (33), while stable proton trapping is estimated to
242 extend up to ~ 5 GeV (41).

243 **Comparison with Saturn's main radiation belts:** It is interesting that proton fluxes in Sat-
244 urn's main radiation belts drop more steeply with increasing energy (11, 24, 42) compared to
245 what we infer for the innermost belt. Several explanations could account for this difference. At-
246 mospheric CRAND in the main radiation belts, which can be generated by high flux, >0.5 GeV
247 primary GCRs (21), is certainly more significant than it is closer to the planet. Magnetospheric
248 radial diffusion becomes increasingly important at larger L-shells (12), where the proton trap-
249 ping limit also drops to the range of ~ 1 GeV. At this stage we cannot exclude that part of the
250 difference seen in the spectra is due to the different LEMMS calibration used in the current and
251 the past studies.

252 **Electron CRAND and additional energetic particle sources:** Our initial survey did not re-
253 veal any unambiguous signature of electrons (presumably from CRAND), at least below 837
254 keV. This suggests that even though CRAND produces electrons, these are lost more efficiently
255 than protons and cannot build up significant intensities. Since several studies indicate that

256 the CRAND source rates at Earth and Saturn are comparable (e.g. (6)), we can use this non-
257 detection and make a rough-order-of-magnitude estimation for the time scales of CRAND elec-
258 tron losses in the inner belt.

259 If we assume that the rate that the 500 keV CRAND electron fluxes increase is $2.5 \times 10^{-2}/(\text{keV}$
260 $\text{cm}^2 \text{sr s})$ in 1.5 hours, as measured at Earth (20), we find that CRAND electrons would exceed
261 the upper detection limits shown in Figure 3B within just 1-2 days. That is a very short time
262 compared to the expected, year-long trapping time scales of such particles that one would ex-
263 pect in the strong, axisymmetric magnetic field near Saturn. The non-detection indicates that
264 18-837 keV electrons are subject to losses which act faster than few days and could develop
265 from electron scattering due to dust and neutrals, from wave-particle interactions, or even weak
266 radial flows, to which electrons are much more sensitive than the protons (43). Such flows may
267 drive CRAND electrons onto the C-ring or the atmosphere within few hours or days following
268 their injection in the trapping region.

269 The very low upper limits for heavy MeV ions set tight constraints also on the intensity of
270 other, non-CRAND related source process that may operate in this region, such as the local pro-
271 duction of energetic light ions through elastic collisions of CRAND protons with atmospheric
272 neutrals (44).

273 **Low altitude, keV proton radiation belt:** The transient character of the low altitude ENA
274 emission confirms that its origin is in the variable ring current (45), as originally suggested (2).
275 The 3800 km altitude limit inferred based on the lack of in-situ keV proton detection when the
276 ENA emission image was obtained (Figure 5) can be further reduced to 2700 km, if we just rely
277 on the value of the lowest L-shell that LEMMS had the appropriate pointing to observe these
278 protons in-situ.

279 The difference with Jupiter is striking. There, keV protons which may have the same origin

280 (charge-stripped ENAs) have fluxes that are 3-5 orders of magnitude above the upper limits
281 estimated for Saturn (5) (Figure 3A). It is possible that the highly structured internal magnetic
282 field of Jupiter (46) enables ions produced through charge stripping in the denser layers of its
283 upper atmosphere to follow drift shells which extend to higher altitudes, where the bounce-
284 averaged density of neutrals that they become exposed to becomes negligible. That could allow
285 ion fluxes to accumulate within less than a drift orbit around the planet and become detectable.
286 The non-axisymmetric terrestrial magnetic field has a similar effect on CRAND electrons, as it
287 allows them to accumulate only at a restricted longitude range where their drift orbit does not
288 intersect the dense layers of our planet's atmosphere (20). The axisymmetric magnetic field of
289 Saturn, on the other hand, restricts ions produced from charge stripping of ENAs to their high
290 atmospheric density generation altitude, severely limiting their lifetime and the extension of
291 their population to the L-shells where MIMI made its in-situ observations.

292 **Conclusions**

293 The Proximal orbits allowed the MIMI instrument to sample one of the few remaining un-
294 explored regions of Saturn's magnetosphere and to complete one of the most comprehensive
295 investigations of a planetary radiation belt other than Earth's.

296 MIMI measurements demonstrate that a radiation belt sector does indeed form inward of
297 Saturn's dense rings, despite the isolation of this region from the rest of the magnetosphere and
298 its collocation with dust and atmospheric neutrals. This radiation belt has two components.
299 The primary one, bound by the planet's atmosphere and the D73 ringlet, originates from ring
300 CRAND, comprises protons with energies extending for ~ 25 MeV and into the GeV range
301 and appears to be stable throughout the five month observation period. Its secondary, low alti-
302 tude component was observed only remotely through ENA imaging, it is transient and contains
303 protons of keV energies.

304 The strong coupling of the primary radiation belt component with Saturn's rings and at-
305 mosphere means that the MIMI measurements presented here will be central for achieving a
306 quantitative description of the CRAND source strength by the main rings and the atmosphere,
307 for probing the physical properties of Saturn's upper atmosphere, and for investigating the D-
308 ring and its three ringlets. The non-detection of a signal from the keV proton population re-
309 sponsible for the ENA emission of the secondary belt, in the context of relevant measurements
310 from Jupiter and Earth, highlights the importance of non-axisymmetric magnetic fields for the
311 formation of low altitude radiation belts through multiple-charge exchange.

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388 performed the response simulations. PK developed and applied the inversion method to ob-
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390 GHJ constructed the graphics for Figure 1 and the Figure of the extended abstract. **Competing**
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392 Cassini/MIMI data and a user guide are available online through NASA's planetary data system
393 (PDS - <https://pds.nasa.gov/>). All raw MIMI data shown here will be released via
394 the PDS within 2018.

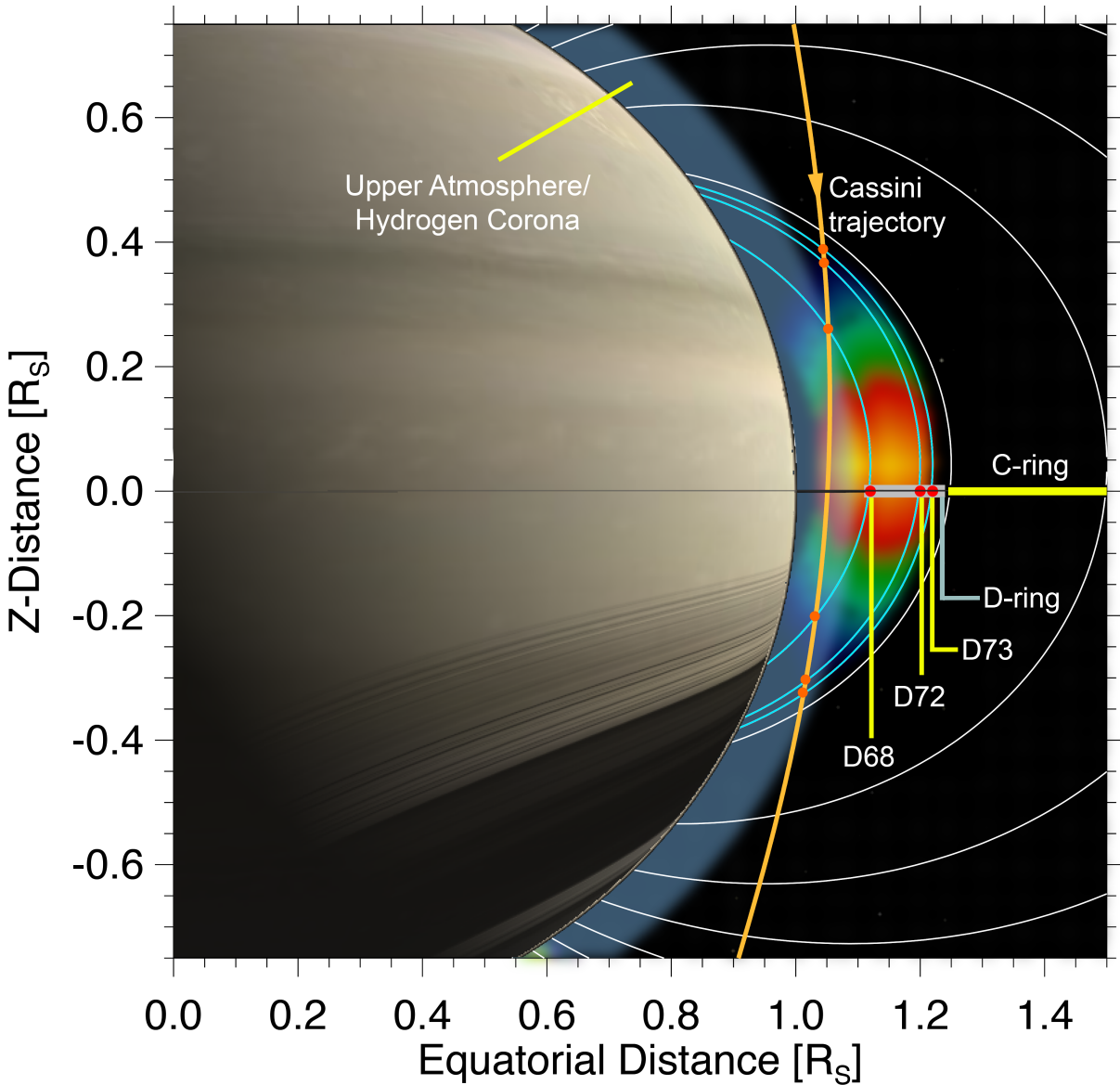


Figure 1: **The geometry of the energetic particle trapping region between Saturn’s rings and atmosphere.** This region is indicated by the color map, which is based on the radial proton flux profile shown later in Figure 4. A typical Cassini Proximal orbit trajectory is shown in orange. Cassini first intersects this region at about 20° north latitude and exits at a similar latitude to the south. As trapped particles move along the magnetic field, Cassini can probe the effects of the D-ring’s dust environment from high-latitudes, without directly crossing through it. The orange circles mark the locations along Cassini’s trajectory where the effects of the D-ring’s ringlets (D68, D72, D73) on the trapped particle population can be transmitted along the magnetic field lines drawn in light blue. Other field lines (in white) are drawn every 0.25 R_S at the equatorial plane.

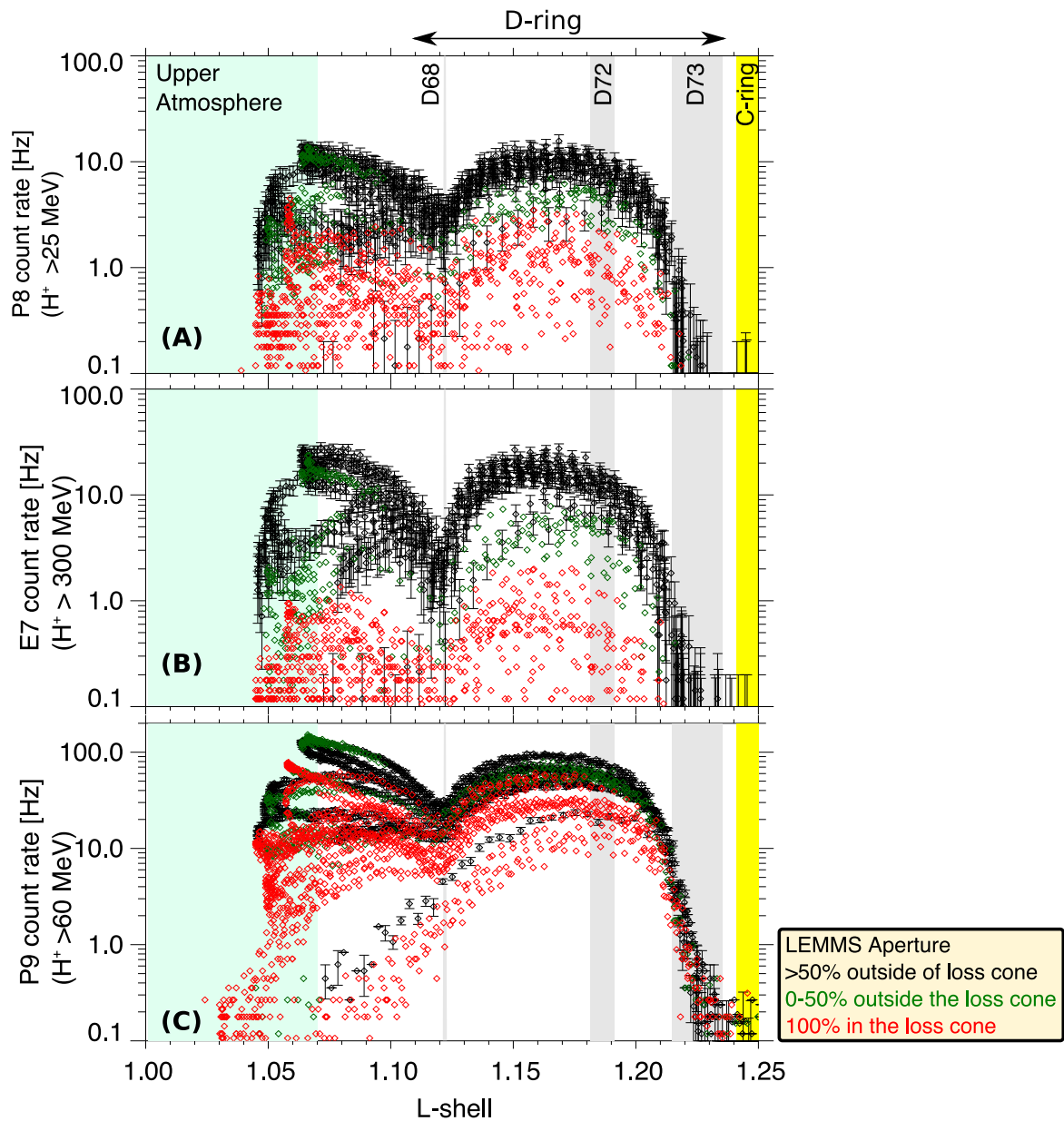


Figure 2: **MIMI/LEMMS count-rates as a function of the L-shell.** Data are obtained from all the proximal orbits (April 23 - September 15, 2017) and for regions mapping magnetically inward of Saturn's C-ring. All channels shown are dominated by protons and cover the energy range above 25 MeV. Count rates are averages of three consecutive samples (one data point per ~ 16 s). The points are color-coded according to the percentage of LEMMS's aperture within the planetary loss cone, as explained in the legend right of Panel (C). It can be seen that the channels in the upper two panels roughly organize with pitch angle, while the channel in the lower panel, representative of most other LEMMS channels not shown here, does not, due to its high-sensitivity to sideways, instrument penetrating protons.

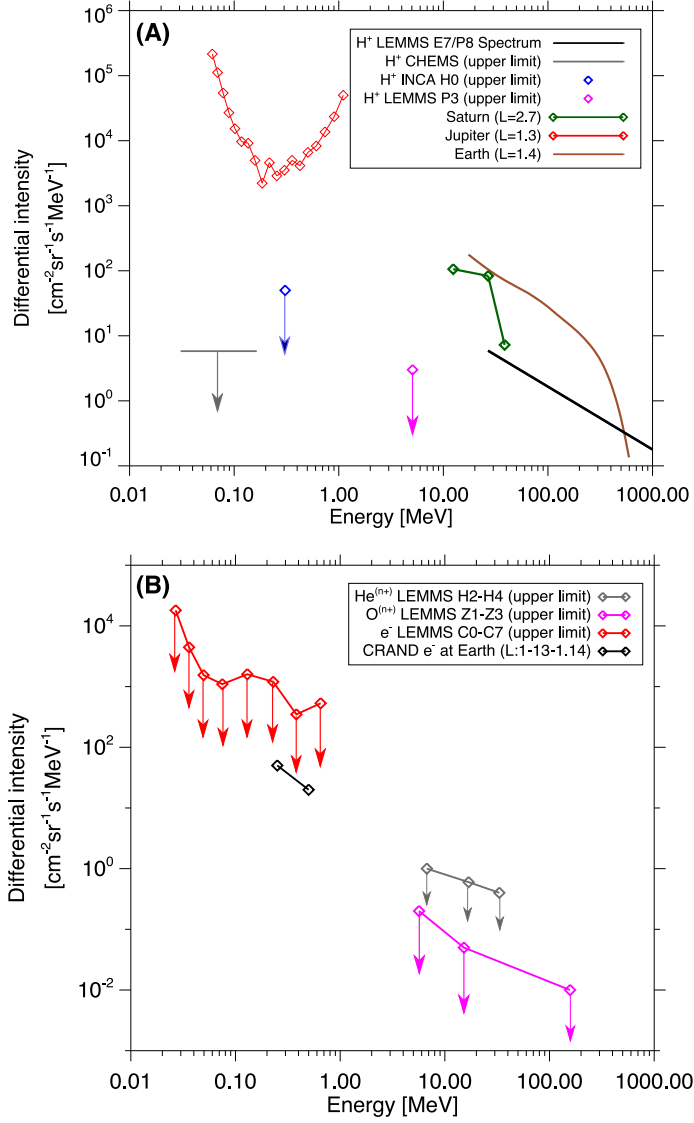


Figure 3: **Energetic particle spectra and upper limits.** Panel A includes a preliminary proton spectrum of 25 MeV to >1 GeV protons (black line). As the PAD of the 25 MeV to ~ 1 GeV protons is highly anisotropic, a pitch-angle averaged spectrum is plotted. All other symbols denote upper flux limits for lower energy protons. For comparison, we also show a proton spectrum from L=1.3 at Jupiter (5), from L=2.4 at Saturn (11) and from L=1.4 ($\alpha_{eq} \sim 90^\circ$) at Earth (40). Panel B shows upper flux limits for ions and electrons. The H2-H4 and Z1-Z3 channels can only constrain the minimum atomic mass numbers of the ions detected ($Z \geq 2$ and $Z \geq 8$, respectively) but we assume these are helium and oxygen. On the horizontal axes, units for protons and electrons are in MeV, for ions in MeV/nuc. The upper limits of electron fluxes can be compared against the maximum electron CRAND fluxes measured at the Earth, based on (20). All Saturn innermost belt measurements are from L=1.1.

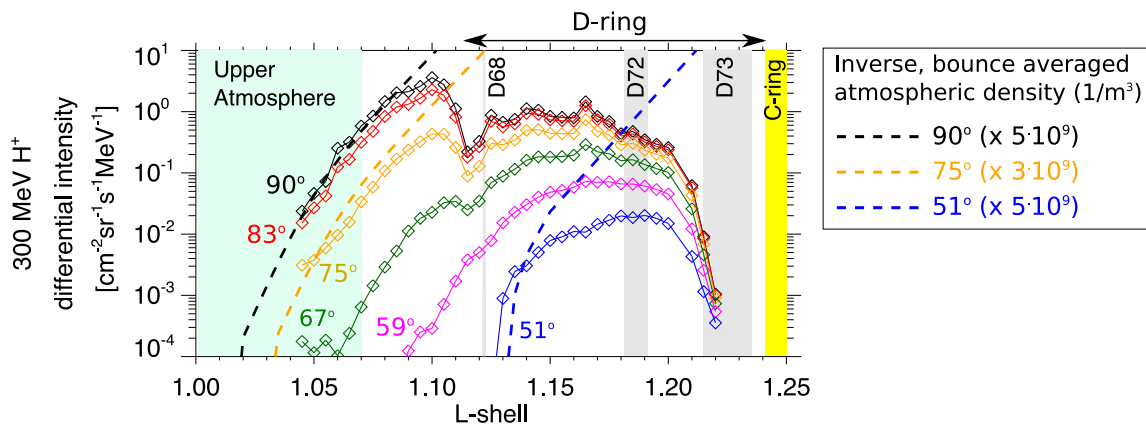


Figure 4: **The L-shell dependence of 300 MeV proton differential intensities.** Different lines and colors correspond to different α_{eq} . Intensities are only shown where the inversion was successful. The progressively smaller extension of the radiation belts for decreasing pitch angles is due to the increasing size of the loss cone towards lower L-shells. The small offset of the central dropout from the L-shell of D68 is probably due to systematic errors associated with the magnetic field model used in this study. Overplotted are three curves showing the inverse of the bounce-averaged atmospheric density (13), scaled by appropriate factors for a better comparison with the proton fluxes. The small difference in the adopted scaling factors is due to the imperfect atmospheric model used.

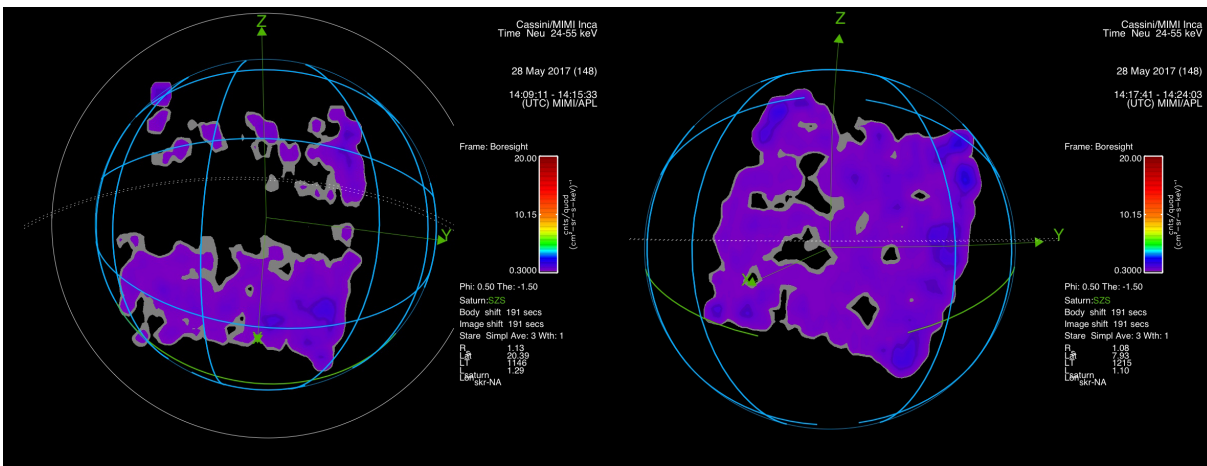


Figure 5: **Imaging of the low altitude ENA emission.** Images of Saturn in 24-55 keV proton ENAs obtained with the MIMI/INCA camera on May 22, 2017. The two frames are taken from the same sequence, with a time difference of 8 minutes. The emission is from the low-altitude keV ion radiation belt, observed also at SOI in 2004 (2). The boundaries of the emission are due to INCA’s field of view. The coordinate system displayed has its origin at the center of Saturn, with the z-axis pointing north, the y-axis towards dusk and along Saturn’s equatorial plane, while the x-axis completes the right-hand system, pointing approximately towards the Sun.

395 **SUPPLEMENTARY MATERIALS**

396 **Materials and Methods**

- 397 • Latitudinal and pitch angle dependencies of proton rates
- 398 • MIMI/LEMMS responses
- 399 • Species Identification
- 400 • Relating Instrument Counts and Intensities

401 **Figures S1-S6**

402 **References 48-59**

403 **Materials and Methods**

404 **Latitudinal and pitch angle dependencies of proton rates**

405 Figure S1.A shows the L and α_{eq} distribution of >300 MeV proton count rates averaged over the
406 22 Proximal Orbits. The features described below apply also to the measurements of >25 MeV
407 protons. The averaged rates tend to increase towards $\alpha_{eq}=90^\circ$ for most of the L-shell range of
408 the trapping region. Simultaneously, count rates experience an increase towards lower magnetic
409 latitudes (Figure S1.B). The latitudinal and pitch angle slopes are very steep: count-rates change
410 by an order of magnitude within just $\sim 5^\circ$ of latitude or $\sim 15^\circ$ of α_{eq} (Figure S.6, (23)).

411 **MIMI/LEMMS responses**

412 In this section we describe new simulations of the LEMMS geometry factors and the procedures
413 that are necessary for the conversion of the raw measured count rates (as in Figure 2) into dif-
414 ferential intensities (as in Figures 3 and 4). The harsh environment of the innermost radiation

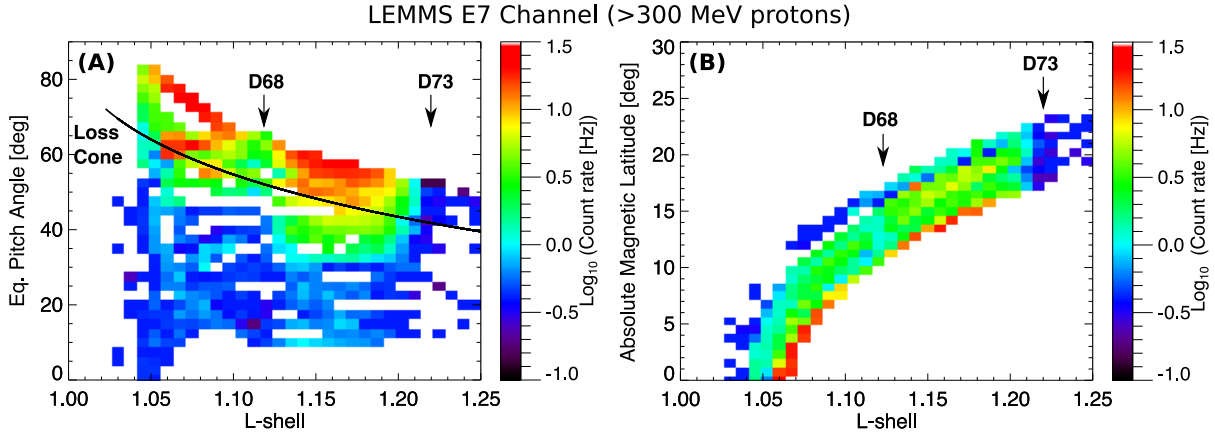


Figure S.1: **Count-rate spectrograms as a function of L-shell, pitch angle and latitude.** Panel (A): L-shell vs. α_{eq} spectrogram of >300 MeV proton count-rates, averaged from all Cassini’s Proximal Orbits. The boundary of the loss cone is overplotted with a black line. Panel (B): L-shell vs. Absolute magnetic latitude spectrogram of >300 MeV proton count-rates.

415 belts as well as the opportunity to resolve the loss cone (and therefore directly separate pen-
 416 etrating radiation from foreground) made us revisit the previous calibration, for which it was
 417 assumed that contribution of instrument penetrating radiation was negligible. The simulations
 418 described below are vital to interpret the data presented in this paper and would likely improve
 419 our understanding of the radiation belts outward of the main rings.

420 **LEMMS simulation setup:** The response simulations of LEMMS were carried out using the
 421 GEANT4 Radiation Analysis for Space (GRAS) software (48, 49). GEANT stands for “Geom-
 422 etry and Tracking”. We constructed a 3d-model of LEMMS using the Geometry Description
 423 Markup Language (GDML). The design, including material assignment to the different volume
 424 elements, was based on archived mechanical drawings of the instrument.

425 The model that we constructed comprises the three main parts of LEMMS: the sensor, the
 426 housing of electronics, and the scan platform (Figure S2.A). It includes most of the sensor’s key
 427 details, namely the distribution of passive shielding by heavy and light material, the geometry

428 of the collimator, and the positions and sizes of the solid state detectors (SSDs). The implemen-
 429 tation of the other two elements (electronics and scan platform) is much simpler but sufficient
 430 (Figure S2, panels B-D). The model mass is 6.45 kg, or 95% of the actual mass of LEMMS
 431 (6.72 kg). The Cassini spacecraft was not included in these simulations.

432 In the LET, separation of electrons and ions is caused by the use of a permanent magnet,
 433 which directs electrons away from the telescope axis and onto detectors E1 and F1. The volume
 434 and the materials of the magnetic assembly (soft iron, samarium-cobalt magnets) are prescribed
 435 in the model, but the magnetic field was not included since we simulated >1 MeV protons, the
 436 trajectories of which are not affected by it.

437 **Geometry factor derivation:** The output of the GEANT4/GRAS simulations was used to
 438 provide the geometry factors of LEMMS as described below. We injected $1.5 \cdot 10^9$ 1 MeV - 5
 439 GeV protons from a spherical surface of radius $r=17$ cm surrounding the instrument model.
 440 A cosine angular distribution was chosen for the source protons. For each proton event we
 441 recorded the ionizing energy losses on the various LEMMS SSDs and applied the coincidence
 442 logic described in (I) in order to obtain the geometry factor, G , for any the instrument's 56
 443 channels, through the following Equation 1 (50):

$$G = 4\pi^2 r^2 \frac{N_C}{N_I} \quad (1)$$

444 N_C is the number of proton events satisfying a channel's coincidence logic, and N_I the
 445 number of injected particles. By binning N_C and N_I over energy, we can obtain the energy
 446 dependence of the geometry factor, $G(E)$.

447 Equivalent to G , we define g_d , as the differential geometry factor, practically the effective
 448 detector area that the protons see if they are injected from within an angular interval of $\theta_1 <$
 449 $\theta < \theta_2$, where θ is the angle between the LEMMS boresight and the proton velocity vector at

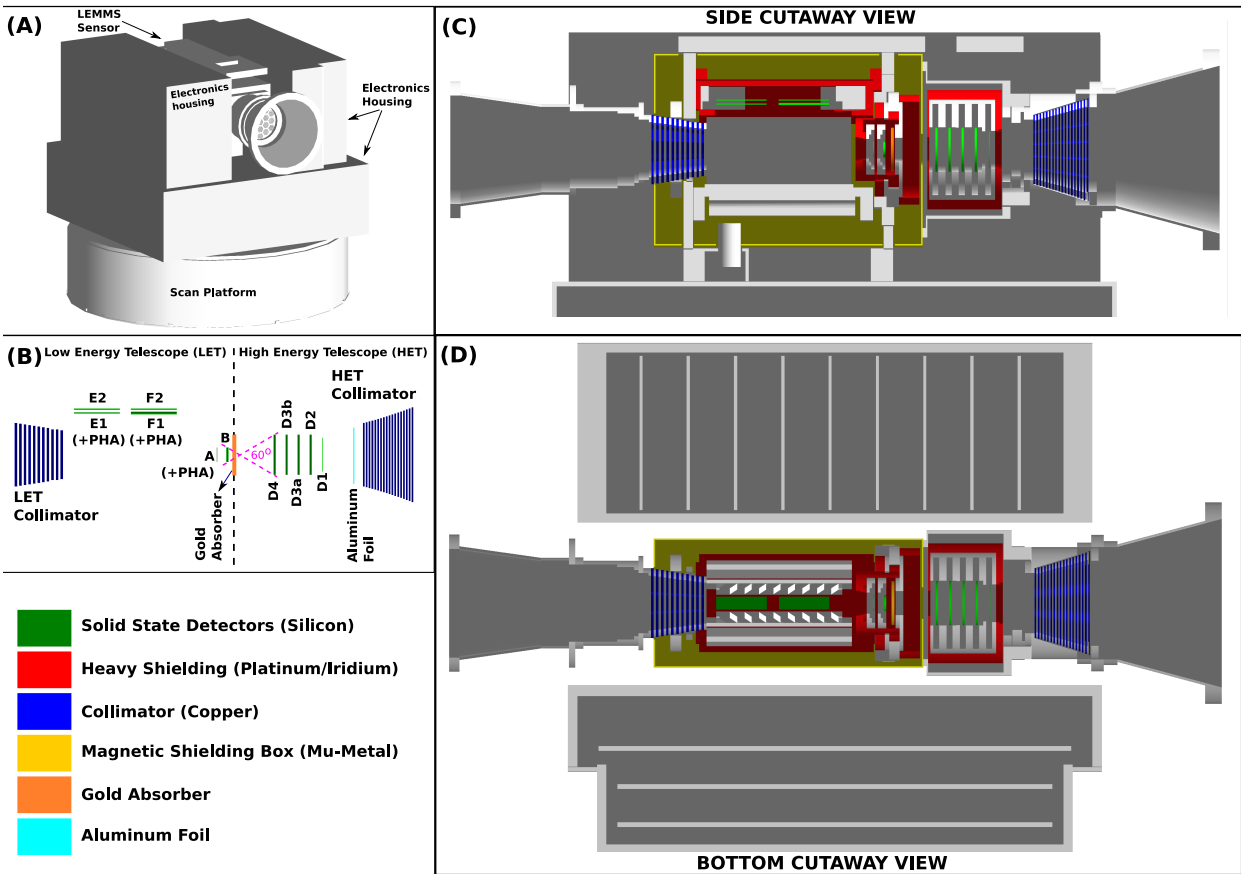


Figure S.2: The LEMMS 3d-model used for response simulations with GEANT4/GRAS. Panel (A): Perspective view of the LEMMS model from the side of the High Energy Telescope (HET). Panel (B): The detector geometry of the LEMMS sensor. Blue lines show the disks that make up the volume of the collimator. The collimators have holes to allow particles to pass. Labels as A, E1, D3a are detector names. Detectors that can perform pulse height analysis measurements (PHA) are also indicated. Electrons reach the E and F detector assembly after being deflected by a permanent magnet within the LET. The opening of the LEMMS collimators is 15° (LET) and 30° (HET). Penetrating particles cannot be collimated and the acceptance angle is greater (e.g. 60° for coincident measurements in the B and D4 detectors - magenta lines). Panels (C) and (D): Side and bottom cutaway views of the LEMMS instrument. The color-coding is explained in the bottom-left side of the figure. Grey volumes are of light material (e.g. aluminum, polyimide for the electronic boards etc.)

450 the source. In that case:

$$g_d = \frac{g}{\Delta\Omega} = \frac{\pi r^2}{(\cos \theta_1 - \cos \theta_2)} \frac{N_c}{N_I} \quad (2)$$

451 where N_c is the number of proton events with $\theta_1 < \theta < \theta_2$ satisfying a channel's coincidence
452 logic. For simplicity we replaced all $\theta > 90^\circ$ with $180^\circ - \theta$, so that g_d becomes the total geometry
453 factor of HET and LET combined. An equivalent expression to Equation 2 can be found in (40)
454 (their Equation 2). Values for G are shown in Figure S.3A, while for g_d in Figure S.3 (panels
455 B-D).

456 **Discussion of the instrument response:** Our simulations validated the energy passbands of
457 LEMMS channels P1-P6 (HET) between 1.4 and 13.4 MeV, that have been used in the previous
458 calibration (24). The geometry factor for all these channels was calculated to be $0.054 \text{ cm}^2\text{sr}$.
459 This number is slightly higher than the one assumed in the previous LEMMS team calibration
460 ($0.040 \text{ cm}^2\text{sr}$). The small difference is due to an improved model of the collimator.

461 For channels P7-P9, which monitor higher energy protons, their calibration requires sig-
462 nificant updates. These channels capture protons penetrating the collimator ($>35 \text{ MeV}$) and
463 the shielding ($>60 \text{ MeV}$) and that increases those channels' acceptance angle and geometry
464 factors and broadens their energy passbands. Our simulations allowed us to also obtain the pro-
465 ton responses of LEMMS's E-channels above 100 MeV, especially for channel E7 that we rely
466 on here for our analysis. The E-channels were designed and so far used to monitor electrons
467 (e.g. (42)).

468 Results for LEMMS channels P8, P9, and E7, the data of which are plotted in Figure 2, are
469 shown in Figure S.3. We can use these simulation results to provide context for the LEMMS
470 measurements. More specifically:

- 471 • The simulations suggest that E7, a channel designed to measure electrons, can also mea-

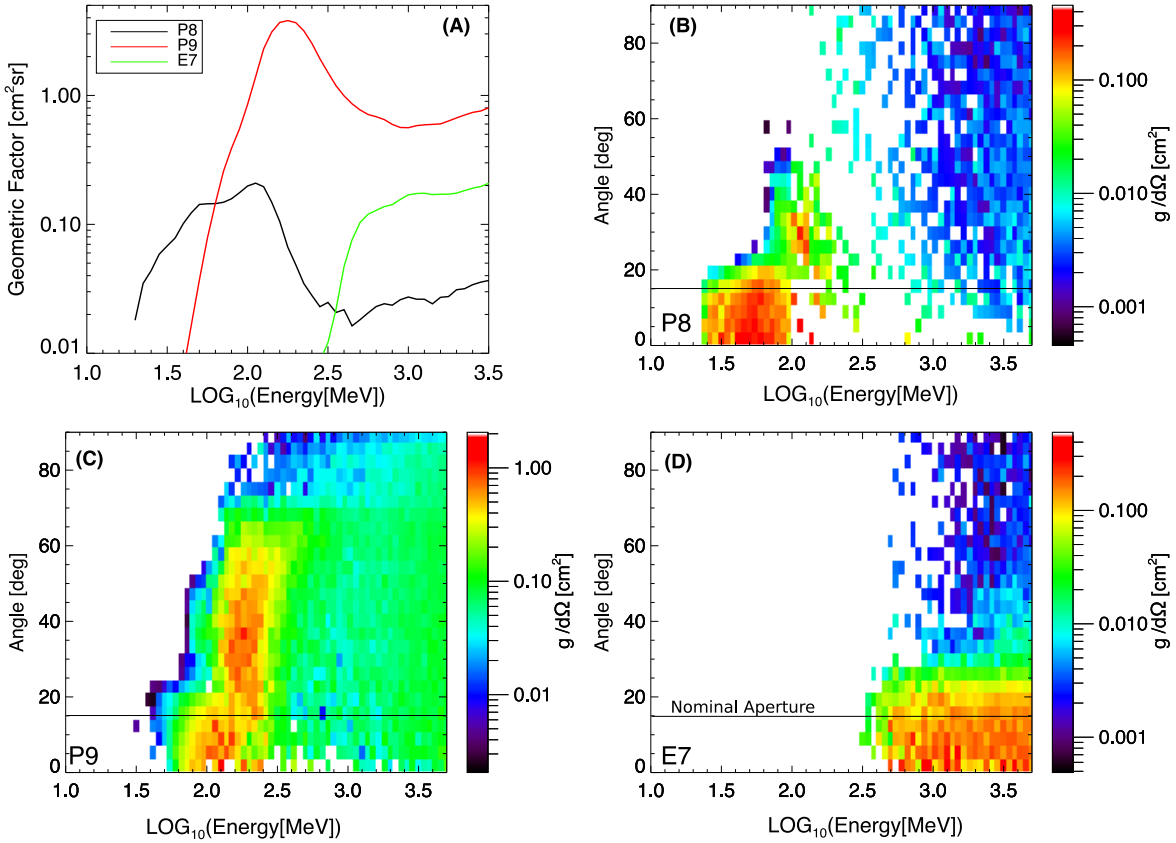


Figure S.3: Results of the proton response simulations for LEMMS channels P8, P9, and E7. Panel (A): Omnidirectional geometry factors G as a function of incident proton energy. Panels (B)-(D): Differential geometry factors g_d as a function of proton energy and incidence angle (θ) with respect to the LEMMS LET or HET boresight. The black horizontal line marks the geometric half opening angle of the HET.

472 sure protons at energies much higher (> 300 MeV) than any of LEMMS's nominal proton
473 channels . A confirmation of this finding with in-flight data is shown in the next subsec-
474 tion of the appendix and Figure S.4. The detector geometry is such that E7 should count
475 protons coming within an acceptance cone of 60° (or 30° half-angle) (Figure S.2B) with
476 respect to the telescope axis. That is very close to the $\sim 25^\circ$ half-angle where E7 has its
477 highest sensitivity based on the simulations (Figure S.3D). The gold absorber between
478 B and D4 limits accidental coincidences by scattered secondaries of high energy protons
479 penetrating at large angles.

- 480 • P8 has an efficient coincidence logic for rejecting penetrating particles, except for the
481 energy range between about 80 and 150 MeV, where a strong secondary response is seen
482 to protons with $25^\circ < \theta < 50^\circ$. That explains why this channel gets more noise from
483 sideways penetrating radiation than E7.
- 484 • P9 has a relatively large geometry factor at all proton energies that it responds to (Figure
485 S.3A). That explains why its count rate is about an order of magnitude higher than those
486 of E7 and P8 (Figure 2C). The relatively high geometry factor of P9 is due to its large
487 sensitivity to sideways penetrating particles: a very strong response is seen for penetrating
488 100-300 MeV protons with incident angles up to 65° . The sensitivity remains high for all
489 angles even above 300 MeV. That clarifies why count rates of P9 in and out of the loss
490 cone are very similar (Figure 2C).

491 **Species Identification**

492 **MIMI/LEMMS observations during Cassini's Earth flyby:** An opportunity to validate the
493 double species response of LEMMS channel E7 with in-flight data is offered through the mea-
494 surements obtained during Cassini's Earth flyby on August 18, 1999 (day 230/1999). Cassini's

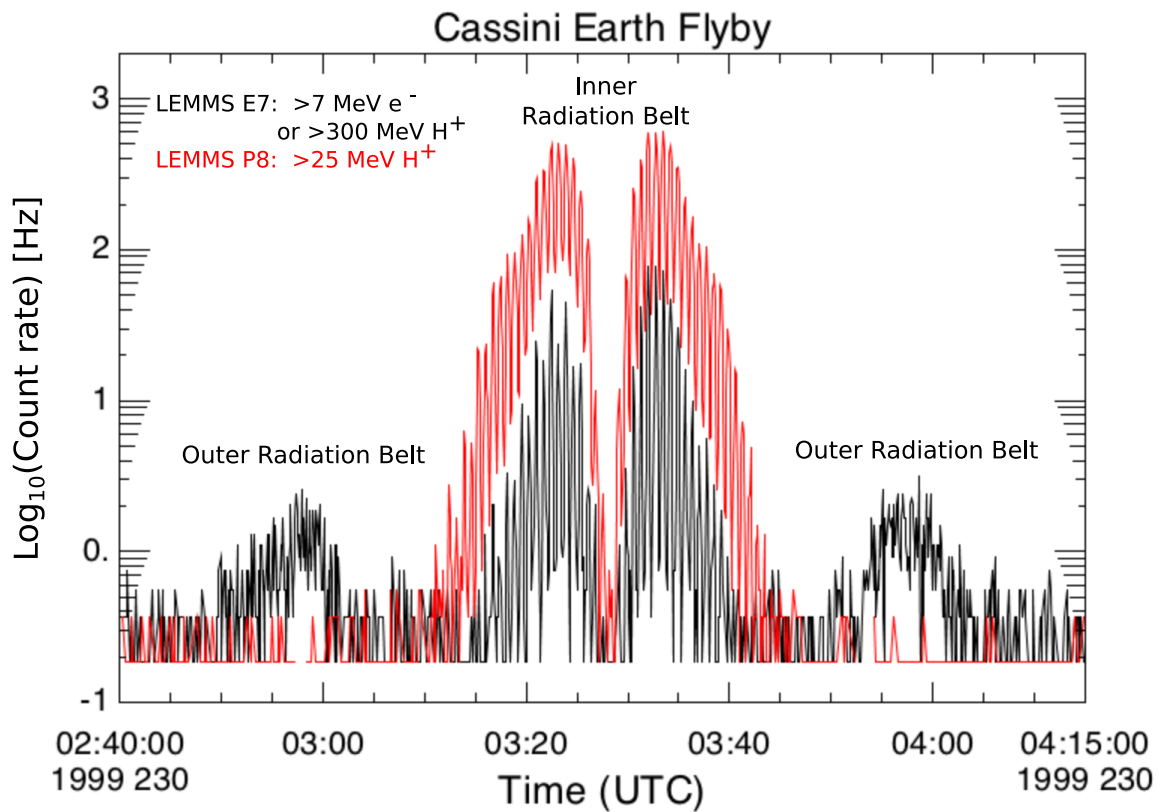


Figure S.4: LEMMS measurements during the periapsis of Cassini’s Earth flyby on August 18, 1999. The rates of two channels are plotted, E7 and P8. The former has a double species response while P8 is a clean MeV proton channel. The periodic modulation of the signal is due to the rotation of LEMMS through its scan platform.

495 closest approach to Earth was 7542 km from its center (or 1.18 Earth radii with $1 R_E=6371$ km)
496 and LEMMS data from its crossing through the Van Allen radiation belts are shown in Figure
497 S.4. Channels E7 and P8 get their peak count rates near the periapsis around 03:27 UTC, when
498 LEMMS was sampling the inner radiation zone. Recent observations showed that this region
499 is dominated by MeV protons, while electron fluxes above 1-2 MeV are negligible (? , ? , ?).
500 Since the E7 channel is sensitive to even higher energy electrons (>7 MeV), its signal between
501 3:15 and 3:45 can only be explained if it also responds to protons, in agreement with what the
502 detector simulations indicate. The similarity with the profile of the proton channel P8 for this
503 30 minute time period also supports this conclusion. The periodic modulation of the signal in
504 these two channels is due to changes in the pitch angle pointing of LEMMS, as its scan platform
505 was operational at that time. The modulation of E7 and P8 signals is in phase, as expected for
506 protons of that region with the characteristic energies measured by these two channels, which
507 have a similar PAD shapes (32).

508 The E7 channel detects a foreground signal also on 02:50-03:05 and 03:50 - 04:05 UTC.
509 In this case, the E7 counts come from >7 MeV electrons of the outer radiation belt (47) rather
510 than protons: the absence of protons is demonstrated by the channel P8, which is at background.
511 These measurements confirm that E7 is a dual-species channel.

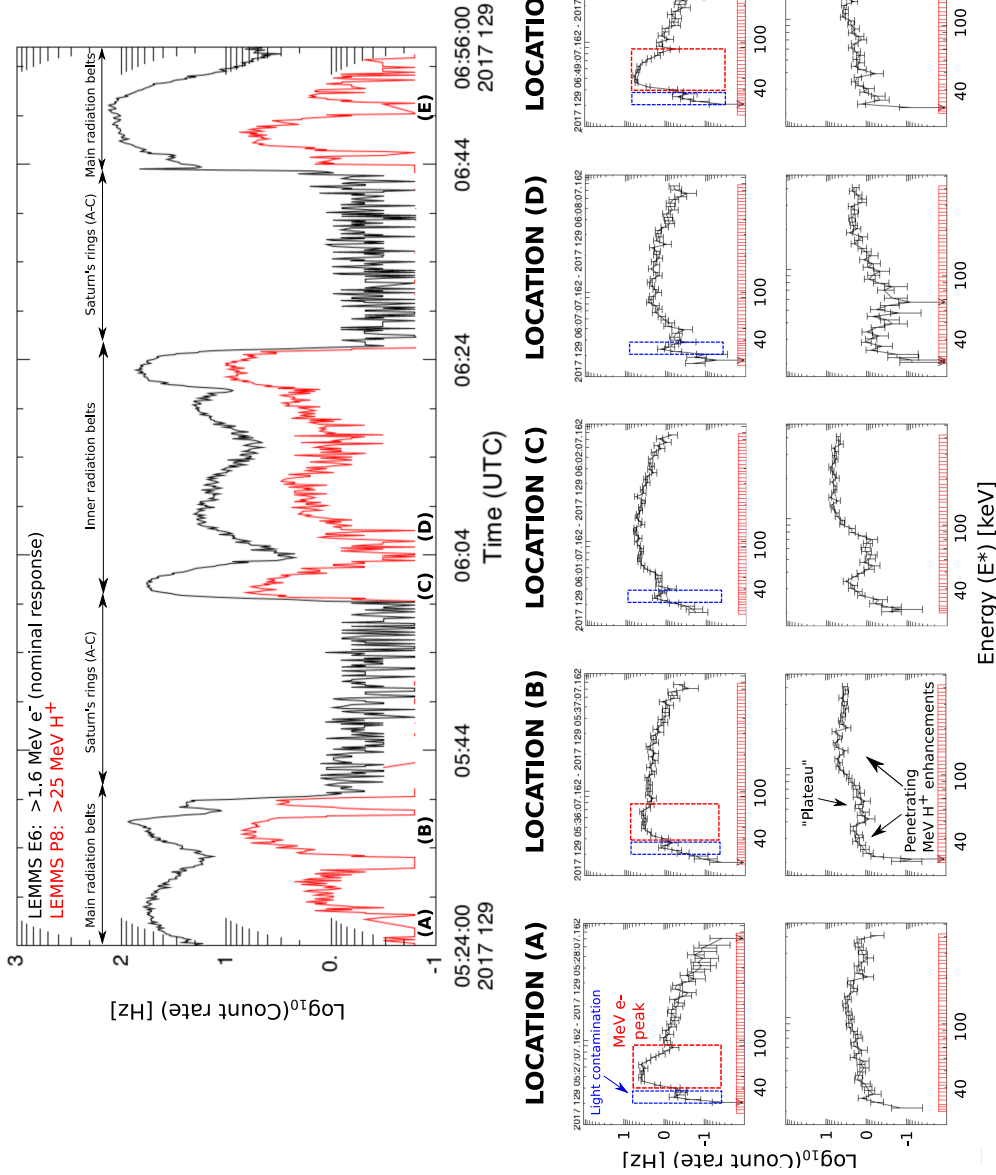


Figure S.5: Top: Time series of LEMMS measurements during the periapsis of Cassini's third proximal orbit (day 129/2017). The rates of two channels are plotted, E6 and P8. The former has a double species response while P8 is a clean MeV proton channel. Several locations (A-E) are marked above the time-axis. Bottom panels: High-resolution PHA spectra at locations A-E, from LEMMS detectors A (top row) and E1 (bottom row). Several spectra features are highlighted and explained in the text. The count-rate spectra are plotted as a function of energy. The energy bins are shown with red on the horizontal axes. We refer to energy as "pseudo-energy" (E^*) since detector counts for the specific interval are due to instrument penetrating particles, for which the correspondence between the pulse-height they cause on the A and E1 detectors and the particles' primary energy is not valid.

512 **High energy resolution spectra of instrument penetrating radiation:** LEMMS achieves
513 high energy resolution particle spectroscopy by applying Pulse Height Analysis (PHA) to the
514 SSD signals. Figure S2.B shows the location of SSDs E1, F1 and A on the LET where PHA
515 spectra can be obtained for energies below 1.2 MeV for electrons (E1 and F1) and 800 keV
516 for ions (A). In the innermost radiation belts, where fluxes of such particles are negligible
517 (e.g. Figure 3), the PHA detectors provide us with high energy resolution spectra of instrument
518 penetrating particles and their secondary products. We analyze these spectra and find that the
519 intensity of energetic electrons in the innermost radiation belts is likely low.

520 Even though the three detectors are positioned within few cm of each other, the shielding
521 distribution around them is different. Furthermore, low energy secondary particles generated in
522 their vicinity may be preferentially focused to certain detectors due to the presence of LET's
523 permanent magnets. As a result, each PHA detector shows a variety of features which we can
524 associate to MeV protons, MeV electrons, or a combination of these two populations.

525 In the top panel of Figure S.5 we show time series of count-rates from LEMMS channel
526 E6 (nominally >1.6 MeV electrons) and P8 (>25 MeV protons) obtained during Cassini's
527 periapsis of the third proximal orbit (day 129/2017). PHA spectra from detectors A and E1 are
528 shown from five time intervals marked on the bottom of that plot (locations A-E). The spectra
529 show count rates as a function of "pseudo-energy", E^* . We call this pseudo-energy because the
530 plotted PHA energy values correspond to the energy that a foreground population of <800 keV
531 protons and <1.2 MeV electrons would have had in order to trigger the A and E1 detectors,
532 respectively.

533 At locations (A) and (E), Cassini samples Saturn's electron radiation belt outside of the
534 main rings. At both locations penetrating radiation is dominated by MeV electrons. MeV
535 protons are absent, as they have been fully absorbed by Enceladus and Mimas, respectively (51).
536 In that case, a characteristic peak at $40 < E^* < 80$ keV and a power-law drop-off at higher

537 pseudo-energies is visible in the PHA-A spectra. In the absence of protons, this signature can
538 be attributed with certainty to MeV electrons. We will search below for such a signature within
539 the innermost belt. In the E1 detector, the pseudo-energy spectrum from MeV electrons is
540 relatively flat with a broad peak centered around 110 keV.

541 Location (B) is still within the main radiation belts, but in a region where both MeV protons
542 and electrons have high contributions. Any qualitative differences with respect to the spectra
543 from locations (A) and (E) are due to MeV protons. We can see that the MeV electron peak in
544 PHA-A is still resolvable, but it is less pronounced because it is superimposed on a count-rate
545 increase from MeV protons in the same E^* range. For $E^* > 80$ keV, the protons make the
546 spectrum flatter and the steep power-law drop-off of the electrons is not visible. In the PHA-E1
547 detector, penetrating MeV protons enhance the count-rates for $E^* < 50$ keV and $E^* > 100$ keV.
548 For $E^* > 100$, the spectrum becomes very flat. The plateau between the two enhancements is
549 then the only resolvable feature which may contain contributions from MeV electrons.

550 After establishing the key signatures of penetrating MeV electrons and protons in the PHA
551 spectra, we can assert which are the dominant species in the inner radiation belts at locations (C)
552 and (D). In location (C) the count-rate of the E6 channel is comparable to the rates measured in
553 the main electron belts at (A), (B) and (E). The same applies for the E6/P8 count-rate ratio. In
554 location (D) the P8 count rate is very low, while E6 has almost a factor 20 stronger signal. If E6
555 gets strong contributions from MeV electrons, the characteristic signatures in the PHA spectra
556 should be observable.

557 Instead, the MeV electron peak in the PHA-A spectra is not visible: count-rates increase
558 above $E^* \sim 60$ keV instead from 40 keV. The steep power-law drop-off at $E^* > 80$ keV is also
559 not present: the flatter spectrum is more consistent with the one at location (B), where MeV
560 protons are present at high fluxes. In the PHA-E1 spectra, the contrast between the MeV proton
561 enhancements at $E^* < 30$ keV and $E^* > 80$ keV and the plateau is much stronger than in location

562 (B), where electrons and protons co-exist. The shallow peak at $E^* \sim 110$ keV attributed to MeV
563 electrons is also not discernible. The spectrum for $E^* > 100$ is flat, a signature of penetrating
564 MeV protons.

565 The signatures in the spectra from the PHA-A and E1 detectors are therefore consistent
566 with a dominant proton population in the radiation belt inward of Saturn’s rings. Since the
567 LEMMS response simulations indicate that the E-channels (including E6, plotted in Figure S.5)
568 can measure > 100 MeV protons, we assert that their signal is dominated by these species.

569 This analysis alone does not exclude the presence of MeV electrons, but rather that their
570 characteristic signatures in the data are obscured by corresponding signatures of protons. The
571 non-vanishing count-rates in the “plateau” feature in the PHA-E1 spectra (location C), may be
572 due to MeV electrons, but that requires a detailed simulation of the spectra, in which case the
573 magnetic field of the LET and the shielding of LEMMS by the Cassini spacecraft have to be
574 added to the model shown in Figure S.2.

575 **Relating instrument counts and intensities**

576 **Inversion process:** In the simple case where the instrument measures particles in a narrow
577 energy and narrow angular range, the conversion of count rates R (particles per time) into the
578 differential intensity j (particles per energy range, solid angle, area, and time) is:

$$j = \frac{R}{G \Delta E} \quad (3)$$

579 where the geometry factor G is given from Equation 1 and ΔE is the effective energy range
580 over which the instrument channel is considered sensitive. Most of the previous work with
581 LEMMS was based on such a calibration.

582 For the environment studied in this paper, Equation 3 is not sufficient because of the pres-
583 ence of high energy protons that can penetrate the instrument housing and shielding. In such

584 cases, many LEMMS channels behave as integral channels and R is estimated by:

$$R(\langle \alpha_{eq} \rangle, \lambda) = \int_0^\pi d\theta \int_0^{2\pi} d\varphi \int_0^\infty dE j(E, \alpha_{eq}) g_d(E, \theta, \varphi) \sin(\theta) \quad (4)$$

585 The differential geometry factor, g_d , was defined in Equation 2, which we derive from the
586 simulations described above and use values illustrated in Figure S.3.

587 The particle kinetic energy is E and the equatorial pitch angle between the instrument
588 boresight vector and the equatorial magnetic field (\vec{B}_{eq}), is α_{eq} . Any quantity in brackets, as
589 $\langle \alpha_{eq} \rangle$, describes a direction along the instrument's boresight. The dependence of α_{eq} on θ and φ
590 is given by combining Equations 5-7 that are described below. We also define λ as the effective
591 latitude that in a dipole field would have the same ratio B_{eq}/B as in our magnetic field model.
592 The latitude definition does not affect the final results.

593 The radiation belt intensity j is usually given as a function of α_{eq} . The relations between
594 equatorial pitch angles α_{eq} and $\langle \alpha_{eq} \rangle$ and the local pitch angles α and $\langle \alpha \rangle$ (relative to the lo-
595 cal magnetic field \vec{B} at latitude λ of the spacecraft) derive from the conservation of the first
596 adiabatic invariant and are:

$$\alpha_{eq}(\alpha, \lambda) = \arcsin \sqrt{\frac{B_{eq}}{B(\lambda)} \sin \alpha} \quad (5)$$

$$\langle \alpha \rangle(\langle \alpha_{eq} \rangle, \lambda) = \arcsin \sqrt{\frac{B(\lambda)}{B_{eq}} \sin \langle \alpha_{eq} \rangle} \quad (6)$$

597 The relation between the local pitch angle (measured relative to the magnetic field) and the
598 angles θ and φ (measured relative to the instrument) depends on spacecraft location λ . This
599 relation can be derived from the cosine law on a sphere, as for example given in Equation 4
600 of (52).

$$\alpha(\theta, \varphi, \langle \alpha \rangle) = \arccos[\cos \langle \alpha \rangle \cos \theta + \sin \langle \alpha \rangle \sin \theta \cos \varphi], \quad (7)$$

601 where $\langle \alpha \rangle$ is the local pitch angle into which the instrument boresight is pointing to. The two
 602 angles α (describing the particle) and $\langle \alpha \rangle$ (describing the instrument) are generally not the same
 603 but can be similar if the particle enters through the nominal opening of the telescope.

604 Before we quantitatively relate the radiation belt intensity j with the raw rate R , it is infor-
 605 mative to point out that these two quantities can have a very different qualitative behavior, as
 606 we find in Saturn’s innermost radiation belt (Fig. 2). Most notably R can show a dependence on
 607 latitude, even when filtering the data for $\langle \alpha_{eq} \rangle$ and L and accounting for reasonable systematic
 608 errors in these quantities. Such a latitudinal dependence is in stark contrast to the behavior of j ,
 609 which is constant for all latitudes along the particle trajectory according to Liouville’s theorem.

610 The latitude dependence of R results from the wide angular response of LEMMS’s high
 611 energy channels, which for the channels considered here extends $\theta > 15^\circ$ away from the center
 612 of LEMMS’s aperture, and the steep PAD in the inner radiation belts.

613 In order to better illustrate this, we consider an extremely wide angular response that can
 614 be described as omnidirectional. At any given latitude, the detector will receive fewer counts
 615 compared to the equator, because particles with certain α_{eq} mirroring at latitudes below the
 616 spacecraft, cannot contribute to the signal of the detector. Effectively, the α_{eq} range covered by
 617 the omnidirectional detector becomes smaller with increasing latitude and therefore the count
 618 rate of the detector decreases. This works similarly for any directional detector, like LEMMS,
 619 with a wide but finite angular resolution, even though the latitude dependence is not usually
 620 as pronounced as it is for omnidirectional detectors. An exception is when the pitch angle
 621 dependence of the intensity j is very steep, i.e. it evolves on angular scales much smaller than
 622 a channel’s angular resolution.

623 In order to convert R into j we use a forward modeling approach. We select a narrow L-

624 shell range and bin the measured count rates of channels E7 and P8 in two dimensions. One
 625 dimension represents the look direction of the instrument. We quantify this with $\langle\alpha_{eq}\rangle$. The
 626 second dimension describes the location of the spacecraft relative to the magnetic equator. For
 627 this, we chose the equivalent latitude λ .

628 Then we assume an intensity distribution $j(E, \alpha_{eq})$ in the radiation belt at this L-shell and
 629 calculate $R(\langle\alpha_{eq}\rangle, \lambda)$ for all bins using Equation 4. The functional form of the intensity, j ,
 630 assumed here is

$$j = A(E) J(\alpha_{eq}) \quad (8)$$

$$A(E) = \left(\frac{E}{E_0}\right)^\gamma \frac{j_A}{1 + e^{(E-10^{E_c})/K_T}} \quad (9)$$

$$J(\alpha_{eq}) = \frac{1 + e^{(C-\alpha_0)/k_t}}{\sin^N \alpha_0} \frac{\sin^N \alpha_{eq}}{1 + e^{(C-\alpha_{eq})/k_t}} \quad (10)$$

633 with $E_0 = 39000\text{keV}$, $K_T = 0.05 \cdot 10^{E_c}$, $\alpha_0 = 90^\circ$, and $k_t = 0.18^\circ$.

634 The function $A(E)$ describes a power-law with exponent γ , with j_A the radiation belt inten-
 635 sity at $E = E_0$ and $\alpha = \alpha_0$. The power law cuts off at energy $10^{E_c} = 20\text{GeV}$. This value was
 636 selected since higher energy protons cannot be trapped around Saturn (30). The function $J(\alpha_{eq})$
 637 describes a pitch angle distribution following a sine-function to the power of N . The distribu-
 638 tion drops sharply into the loss cone inward of angle C . The loss cone angle is calculated for
 639 each location based on the chosen magnetic field model.

640 Based on the assumed intensity distribution (Equation 8) we numerically calculate recon-
 641 structed rates R_r for each bin (Equation 4) and compare with the measured rates R_m for each
 642 respective bin. The discrepancy between R_r and R_m is quantified via the root-mean-square
 643 (RMS) error $\Delta = \sqrt{\sum_i^I (\delta)^2 / I}$ with $\delta = \log R_r^i - \log R_m^i$, where i runs over all I bins and
 644 channels. The free parameters are iterated until a good match between modeled and measured
 645 rates is found. The iteration is done using the CONSTRAINED_MIN function available in the

646 commercial software Interactive Data Language (IDL by Harris Geospatial Solutions, Inc.). Af-
647 ter optimization, we find RMS errors of $\Delta < 0.1$, equivalent to the model rates being between
648 $1/10^\Delta = 80\%$ and $10^\Delta = 130\%$ of the measured rate. The maximum error in a single bin is
649 always $\delta < 1$.

650 We compare sample model and measured rates as a function of pitch angle and latitude in
651 Figure S.6 (panels A-D). Panels E and F compare all binned, measured rates with the recon-
652 structed count rates. The resulting differential intensities are plotted in Figures 3 and 4. It can
653 be seen that the reconstruction reproduces all rates of any magnitude similarly well.

654 **Upper flux limits:** The method used to obtain the upper flux limits for non-proton species
655 and for <25 MeV protons shown in Figure 3 is explained with the help of the data plotted in
656 Figure S.7. The channel used in this example has a nominal response to 510-832 keV electrons
657 (C7). All panels include data obtained between $L=1.095$ and $L=1.105$, where the intensity is
658 highest.

659 The C7 measurements are well organized as a function of magnetic latitude (Figure S.7A)
660 and shows an isotropic PAD (Figure S.7D), even in the loss cone, for every latitude. That
661 is a typical behavior of a channel which is dominated by penetrating radiation from trapped
662 particles. . In contrast, a channel with a high SNPR, like E7 that has been extensively used
663 here, has a much more scattered count-rate distribution over latitude (Figure S.7C). This scatter
664 at any selected, small latitude range is due to the superimposed pitch angle dependence of the
665 signal.

666 The uncertainty for the strength of the residual signal outside the loss cone, after we subtract
667 the penetrating radiation rate, is determined by the 1σ value of the count rates at the given L-
668 shell. It is this value that we use in order to obtain the upper limits of Figure 5. In the case of
669 channel C7, its rate varies between 1.4-2.0 Hz, depending on the latitude range chosen. A value

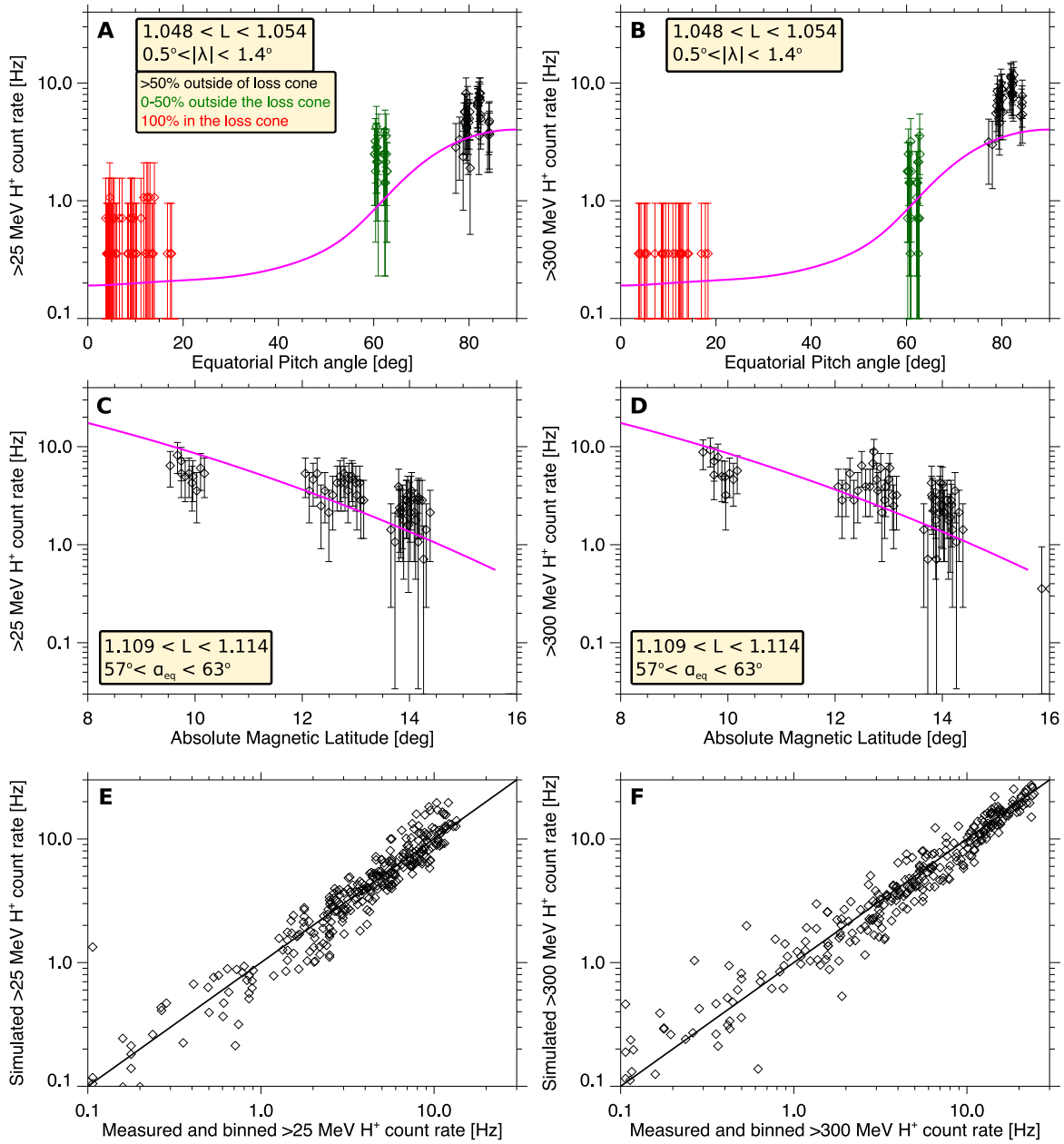


Figure S.6: Comparison of measured and reconstructed count rates. Left and right panels are for >25 MeV and >300 MeV protons, respectively. The model results are shown with a magenta curve in Panels A-D. Panels A and B show data selected from a narrow L-shell and magnetic latitude range, while data in C and D are from a narrow L-shell and α_{eq} range. In panels E and F we compare data from all L-shells (assembled in small L-shell, magnetic latitude and α_{eq} bins) with the simulated rates.

670 of 1.7 Hz was used for Figure 3. Conversion of this count-rate to an upper flux limit is done
671 through Equation 3. These limits are accurate to about 30%. The same approach was used with
672 all other LEMMS channels shown in Figure 3.

673 Limits for the electron fluxes in the MeV range could not be derived, but have to be small
674 because even the respective LEMMS channels appear to be dominated by protons. Proton
675 dominance is indicated by the E7 channel (>300 MeV protons and >7 MeV electrons) showing
676 gross similarities in its L-shell profile with the P8 channel (>25 MeV protons, no electrons).

677 For CHEMS protons, we estimate a total sampling time of ~ 384 minutes in the inner trap-
678 ping region. The mass (M) to mass-per-charge (M/Q) event matrix revealed no accumula-
679 tion of proton counts, so assigning a single count to protons as an upper limit is a reason-
680 able guess. Since the energy stepping in CHEMS lasts 32 s, for each proton energy the sam-
681 pling time was $(384*60 \text{ s})/(32 \text{ s}) = 720 \text{ s}$, which, using Equation 3, translates to a flux of 5.8
682 $\text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}\text{MeV}^{-1}$ for the 27-220 keV energy range where triple coincidence measurements
683 are possible. This upper limit can be used for any ion species that CHEMS can resolve, not just
684 protons.

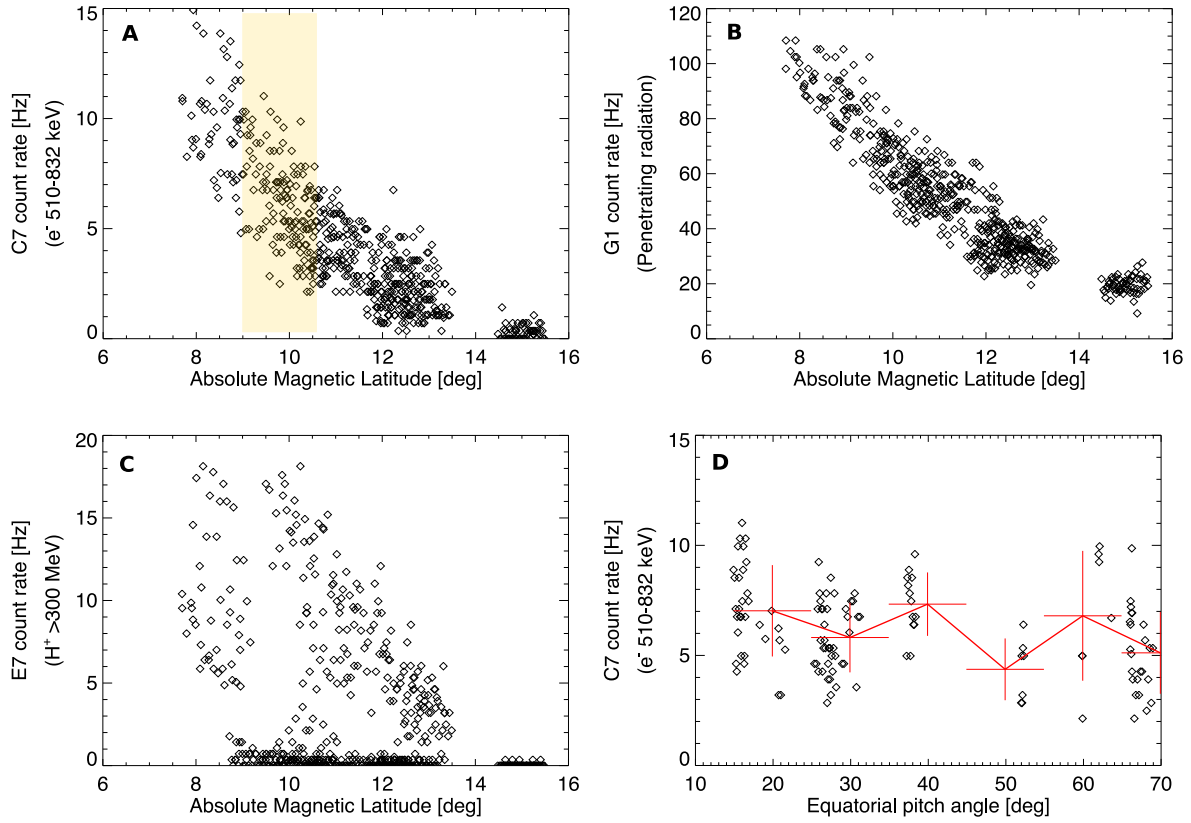


Figure S.7: Illustration on the derivation of the upper limit intensities shown in Figure 5: Panel (A): Magnetic latitude dependence of LEMMS C7 count rates (510-832 keV e^- nominally). Panel (B): Magnetic latitude dependence of LEMMS channel G1 rates, a channel that is designed to measure only penetrating radiation, Panel (C): Magnetic latitude dependence of LEMMS channel E7, without α_{eq} filtering, Panel (D): Dependence of C7 count rates over α_{eq} , for the latitude range marked with the shaded area in Panel A. Binned rates every 10° of α_{eq} are also shown in red.

685 **References and Notes**

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