

1 **On the dynamics of ultra-relativistic electrons (>2 MeV) near $L^* = 3.5$ during**
2 **8 June 2015**

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15 **Key points**

- 16 1. A local minimum in >2 MeV electron phase space density is shown to form rapidly near
17 $L^*=3.5$ during a moderate storm of minimum $Dst=-67$ nT
- 18 2. EMIC wave characteristics are shown during this event, and we use quasi-linear theory to
19 evaluate their role in this loss
- 20 3. Pitch-angle diffusion simulations with scattering rates due to O+ band EMIC waves are
21 shown to reproduce the observed loss at $L^*=3.5$

22 **Abstract**

23 Understanding local loss processes in Earth's radiation belts is critical to understanding their
24 overall structure. Electromagnetic ion cyclotron waves can cause rapid loss of multi-MeV
25 electrons in the radiation belts and contribute to an uncommon three-belt structure in the radiation
26 belts. These loss effects have been observed at a range of L^* values, recently as low as $L^* = 3.5$.
27 Here, we present a case study of an event where a local minimum develops in multi-MeV electron
28 phase space density near $L^* = 3.5$ and evaluate the possibility of EMIC waves in contributing to
29 the observed loss feature. Signatures of EMIC waves are shown including rapid local loss and
30 pitch angle bite outs. Analysis of the wave power spectral density during event shows EMIC wave
31 occurrence at higher L^* values. Using these representative wave parameters, we calculate
32 minimum resonant energies, diffusion coefficients, and simulate the evolution of electron PSD
33 during this event. From these results, we find that O⁺ band EMIC waves could be contributing to
34 the local loss feature during this event. O⁺ band EMIC waves are uncommon, but do occur in these
35 L^* ranges, and therefore may be a significant driver of radiation belt dynamics under certain
36 preconditioning of the radiation belts.

37 **1. Introduction**

38 Earth's radiation belts are normally a two-belt structure of energetic particles, with an inner
39 belt which consists primarily of 100s of keV electrons and 10s to 100s of MeV protons with peak
40 fluxes at $L \approx 2-3$, and an outer belt of mainly 100s of keV to >MeV electrons with peak intensity
41 near $L = 4-5$. L is the McIlwain L value, the distance in Earth radii (R_E) at which a dipole field line
42 crosses the geomagnetic equatorial plane (McIlwain, 1961). The high energy electron populations
43 in the outer belt exhibit various dynamics due to solar driving of the magnetosphere. The Van
44 Allen Probes (formerly known as Radiation Belt Storm Probes, or RBSP) mission has provided

45 valuable insight to the behavior of these energetic particles (Mauk et al., 2012). One of the early
46 discoveries of the Van Allen Probes era was the identification of a third radiation belt, a storage
47 ring of multi-MeV electrons near the inner edge of the outer radiation belt which is not generally
48 observed (Baker et al., 2013). This was characterized by a reduction in flux of multi-MeV electrons
49 in the region $3.5 < L^* < 4.0$ resulting in local peaks in fluxes in the region $3.0 < L^* < 3.5$ and at
50 $L^* > 4.0$. L^* is the Roederer L value and is inversely proportional to the third adiabatic invariant
51 (Roederer 1970), and $L^* \approx L$ for the low values of interest discussed here, although their unit is
52 different (Roederer and Lejosne, 2018, Xiang et al., 2017).

53 Various driving mechanisms in the inner magnetosphere cause dynamics of trapped particle
54 populations. Here, we highlight effects most prevalent in the dynamics of these multi-MeV
55 electrons in the radiation belts. Phase space density (PSD) is often used to visualize these
56 mechanisms, which is related to particle flux divided by the square of the particle's momentum
57 (e.g., Chen et al., 2006). Trapped particles will undergo radial diffusion, a process referred to as a
58 random walk due to varying electric and magnetic fields around the Earth (e.g., Barker et al., 2005;
59 Lesjone et al., 2020). Radial diffusion will cause particles to reduce local radial gradients that
60 develop in PSD (e.g., Green & Kivelson, 2004). The Dst effect changes the drift orbit radius of
61 trapped particles during geomagnetic storms, as drift shells increase in radius to conserve the third
62 adiabatic invariant in response to the reduction in Earth's magnetic field strength, resulting in a
63 measured reduction in flux at a fixed radial distance as particles move outward (Kim & Chan et
64 al., 1997; Li et al., 1997). This process is an adiabatic process and PSD will reverse to pre-storm
65 levels with the recovery of Dst. Magnetopause shadowing is another driver of dynamics which
66 occurs during storms when the solar wind compresses Earth's magnetosphere inward and reduces
67 the last closed drift shell (LCDS) (e.g., Turner et al., 2014, Xiang et al., 2018). Particles outside of

68 the LCDS are lost and particles near the LCDS are then exposed to rapidly formed gradients in
69 PSD due to the outward loss of particles. Earthward particles of the LCDS then radially diffuse
70 outward toward the gradient near the magnetopause and can also be lost outward of Earth's
71 magnetosphere.

72 Wave-particle interactions can also cause loss of radiation belt populations and are energy-
73 dependent due to resonance conditions with the timescales of invariant motions of trapped
74 particles. Chorus waves can cause precipitation of MeV electrons on timescales of several days
75 (Orlova & Shprits, 2014). Chorus wave loss is generally observed outside of the plasmasphere, a
76 region of dense cold plasma with a varying outer boundary generally confined to $L < 4$ (e.g., Thorne
77 2010). Hiss waves are observed within the plasmasphere and can preferentially scatter several
78 hundreds of keV electrons (e.g., Ni et al., 2019; Zhao et al., 2019). Hiss waves can also cause weak
79 loss of MeV electrons on timescales of days to months (Malaspina et al., 2016; Selesnick et al.,
80 2003; Thorne et al., 2013). Another type of wave which prominently affects MeV energy electrons
81 are electromagnetic ion cyclotron (EMIC) waves (e.g., Summers et al., 2007). EMIC waves effects
82 are observed as fast, local losses of multi-MeV electrons satisfying resonance conditions (e.g.,
83 Aseev et al., 2017; Drozdov et al., 2019, 2020, 2022; Shprits et al., 2016, 2017; Usanova et al.,
84 2014; Xiang et al., 2017). Local extrema which form due to these loss processes can result in
85 radiation belt features such as the third radiation belt. The three-belt structure first reported by
86 Baker et al., (2013), with a storage ring of multi-MeV electrons found near the inner edge of the
87 outer belt, is shown to be reproduced in simulation models only with the inclusion of EMIC wave
88 effects (Shprits et al., 2016). Therefore, understanding the effects of EMIC waves on multi-MeV
89 electron populations near the inner edge of the outer belt is critical to understanding the overall
90 structure of the radiation belts. Their effects on multi-MeV electrons are characterized in recent

91 studies using the rich data collected by the Van Allen Probes Relativistic Electron Proton
92 Telescope (REPT) data, with notable features such as multi-MeV electron loss by up to 2 orders
93 of magnitude within satellite passes, limiting electron lifetimes, and producing bite outs in the
94 pitch angle spectra (Baker et al., 2021; Su et al., 2017). We present here a discussion of the EMIC
95 wave loss mechanism.

96 EMIC waves pitch angle scatter electrons into the loss cone via doppler-shifted resonance with
97 electrons (Thorne and Kennel, 1971). EMIC waves most easily scatter particles at low equatorial
98 pitch angles already near the loss cone, and narrowing of the pitch angle spectra, or “bite-out”
99 features in multi-MeV electron flux have been shown to accompany EMIC wave occurrences (e.g.,
100 Aseev et al., 2017; Usanova et al., 2014). However, these studies have not made efforts to
101 numerically quantify the relationship between flux evolution due to EMIC waves and the
102 development of these bite outs. To decrease the entire pitch angle spectra, other waves that have
103 stronger effects at all pitch angles such as chorus and hiss waves are likely required in concert with
104 EMIC waves to produce whole-spectra losses (Drozdov et al., 2020; Ross et al., 2021). EMIC
105 waves can only affect electrons of above specific energies, described as the minimum resonant
106 energy of the electrons (e.g., Summers & Thorne, 2003). The minimum resonant energy as a
107 function of pitch angle is dependent upon the solution of the plasma dispersion relation describing
108 the wave behavior in the local plasma environment. Local loss processes such as EMIC wave
109 scattering are apparent in radial PSD profiles as rapid decay at a specific L^* value where the EMIC
110 waves are present which can induce local minimums.

111 However, variations in L^* locations of EMIC wave effects on multi-MeV electrons are
112 reported; for example, at $L^* = 4.0$ (Shprits et al., 2017, 2022), at $L^* = 4.2$ (Lyu et al., 2022), $L^* >$
113 4.2 , (Xiang et al., 2017), $L^* = 4.5$ (Usanova et al., 2014), and at $L^* = 4.7$ (Aseev et al., 2017)

114 during various events. A study of Van Allen Probes and GOES observations by Drozdov et al.,
115 (2022) showed that local PSD minimums are most common for several-MeV electron populations
116 in the range $L^* = 4-5$. Furthermore, the PSD minimums reported by the study by Drozdov et al.,
117 (2022) were reproduced only with EMIC wave effects included in a simulation model. A study by
118 Cervantes et al., (2020) of Van Allen Probes data from October 2012-2016 found that EMIC waves
119 on average affect $\mu \geq 900$ MeV/G electrons in the range $L^* = 3.6 - 6$ and are the dominant loss
120 process during storms near the inward edge of multi-MeV electron loss observations. Clearly,
121 variations exist in the spatial extent of EMIC wave induced PSD minimums of multi-MeV
122 electrons. Furthermore, the inward location of these PSD features and their driving mechanisms
123 must be understood due to their contributions of local minimums in multi-MeV electron
124 populations which contributes to the formation of the three-radiation belt structure. Hogan et al.,
125 (2021) reported an energy-dependent local minimum in multi-MeV electron PSD that forms over
126 a long-term period from March to June 2015 near $L^* = 3.5$, lower than where EMIC wave-induced
127 loss has been reported before with event studies. PSD minimums in this L^* region can be difficult
128 to find with automatic detection algorithms such as those used by Drozdov et al., (2022) due to
129 low PSD at small L^* values. The dwell time of the spacecraft also decreases at low L^* value,
130 making the occurrence of these features less likely to be reported (e.g., Chen et al., 2019, Saikin
131 et al., 2015, Sigsbee et al., 2023).

132 Statistical studies of EMIC wave occurrence during the Van Allen Probes era describe the
133 spatial occurrence and frequency of these waves. Saikin et al., (2015) compiled EMIC wave
134 observations using Van Allen Probes data from 2012-2015 and Sigsbee et al., (2023) studied the
135 same data set until June 2016. Both studies showed that most observations of H⁺ and He⁺ band
136 EMIC waves occur between $L = 4-6$, and O⁺ band waves are mostly observed at $L < 2-4$. Chen et

137 al., (2019) studied the Van Allen Probes data set until 31 December 2017 and reported H⁺, He⁺,
138 and O⁺ band EMIC waves to occur primarily in the regions $5 \leq L \leq 6.5$, $3 \leq L \leq 4.5$, and $3 \leq L \leq$
139 4 for each species. The majority of EMIC events, regardless of wave band, occur in the region $5 \leq$
140 $L \leq 6$, with 35% of EMIC waves observed are in the H⁺ band, 59% were He⁺ band, and 7% were
141 O⁺ band waves (Saikin et al., 2015). Sigsbee et al., (2023) report EMIC waves are observed ~2.4%
142 of the time during the Van Allen Probes era, considering data from both Probes. Studies by Yu et
143 al., (2015) suggest that O⁺ band waves can grow strongly near the plasmopause boundary region
144 where the oxygen torus forms (e.g., Nosé et al., 2015), thus their increased observational
145 occurrence in the low L region.

146 This study analyzes a moderate storm on 8 June 2015 during which Hogan et al., (2021)
147 reported the formation of a local minimum in PSD in March-June 2015 at $L^* = 3.5$, lower than
148 where EMIC wave-induced local minimums had been reported before and lower than where the
149 more common H⁺ and He⁺ EMIC waves are generally observed. We investigate the physical
150 mechanism responsible for this local minimum by analysis of multi-MeV electron measurements,
151 wave observations by the spacecraft, and consideration of wave particle interaction theory for the
152 local plasma environment. PSD and flux features shown during the event are consistent with prior
153 observations and theory of multi-MeV electron interactions with EMIC waves. EMIC waves in
154 the O⁺ band will be shown to be the most likely contributor of this minimum from analysis using
155 wave-particle interaction theory. Analysis of the wave power spectral density during the event is
156 conducted and calculation of minimum resonant energies and diffusion coefficients for
157 representative EMIC waves during the event are found. These diffusion coefficients are then used
158 in a one-dimensional pitch-angle diffusion simulation to model the effects of EMIC waves during

159 the event of study, showing the feasibility of O⁺ band EMIC waves in contributing to the observed
160 loss. We discuss these results and present conclusions for the reader.

161 **2. Instrumentation and methods**

162 **2.1. Data**

163 Data from the Van Allen Probes mission is utilized for this study (Mauk et al., 2012). The Van
164 Allen Probes consisted of two nearly identical probes launched into near-identical following orbits
165 on 30 August 2012 and provided near-continuous measurements of the radiation belts until 18
166 October 2019 (Probe A) and 19 July 2019 (Probe B). Various onboard instruments provided
167 simultaneous measurements of particles and waves in the radiation belts. The Energetic Particle
168 Composition and Thermal Plasma Suite (ECT) provided energetic particle measurements and
169 included the Relativistic Electron Proton Telescope (REPT) instrument (Baker et al., 2012). REPT
170 provides >MeV electron energy measurements with high count rates, even at low L values where
171 fluxes are low, due to its large geometric factor (0.2 cm²sr). We use this electron flux data to
172 calculate electron PSD (e.g., Chen et al., 2006). The ECT Magnetic Ephemeris files (MagEphem)
173 are also utilized here, in which adiabatic coordinates have been computed for selected magnetic
174 field model configurations. Here, we use calculated adiabatic coordinates found using the TS04D
175 magnetic field model, which should account for storm-time differences in the magnetic field
176 (Tsyganenko & Sitnov, 2005). Magnetometer data from the Electric and Magnetic Field
177 Instrument Suite and Integrated Science (EMFISIS) (Kleitzing et al., 2013) is inspected using
178 methods for analyzing a tri-axial magnetometer (Bortnick et al., 2009; Usanova et al., 2012). We
179 also use data from EMFISIS for obtaining an estimate of the local number density of electrons
180 from analysis of the observed upper-hybrid frequency, identification of the plasmopause boundary,
181 and determining the local magnetic field strength.

182 **2.2. Theory**

183 Wave-particle interaction theory predicts the energy exchange behavior of a wave and a
 184 trapped particle's invariant motion. L-mode EMIC waves are expected to have doppler-shifted
 185 gyroresonance with electrons of given energies (Kennel and Thorne, 1971). This is true when the
 186 following resonance condition is satisfied:

$$187 \quad \omega - kv_{\parallel} = N|\Omega_e|/\gamma \quad (1)$$

188 where ω is the frequency of the wave, k is the parallel wave number found from the plasma
 189 dispersion relation, N is the cyclotron resonance harmonic, Ω_e is the electron gyrofrequency, $\gamma =$
 190 $(1 - v^2/c^2)^{-1/2}$ is the Lorentz factor, $v = (v_{\parallel}^2 + v_{\perp}^2)^{1/2}$ is the electron speed, and v_{\parallel} and v_{\perp} are
 191 the velocity components parallel and perpendicular to the ambient magnetic field. The minimum
 192 energy of electrons E_{min} (in units of $m_e c^2$) that will have gyrofrequencies which satisfy resonance
 193 this resonance condition is:

$$194 \quad E_{min} = [1 - (v_{\parallel}/c)^2]^{-1/2} - 1 \quad (2)$$

195 where v_{\parallel}/c is the ratio of the particle's parallel velocity v_{\parallel} to the speed of light c , and v_{\parallel} is found
 196 via the solution of equation (1) which therefore depends on the solution of a plasma dispersion
 197 relation (e.g., Summers & Thorne 2003). Here, we assume a cold plasma dispersion relation as
 198 described by Summers & Thorne (2003) and Summers et al., (2007). The strength of pitch angle
 199 scattering by L-mode EMIC waves can also be quantified by quasi-linear interaction theory as
 200 described by the pitch angle diffusion coefficient $D_{\alpha\alpha}$ as described by Summers et al., (2007)
 201 for these waves is:

$$D_{\alpha\alpha} = \frac{\pi}{2} \frac{1}{\rho} \Omega_e^2 \frac{1}{(E+1)^2} \sum_j \frac{R(1 - \frac{x_j \cos \alpha}{y_j \beta})^2 |dx_j/dy_j|}{\delta x |\beta \cos \alpha - dx_j/dy_j|} e^{-\frac{(x_j - x_m)^2}{\delta x^2}} \quad (3)$$

202 where ρ describes the Gaussian spectral density of the wave, Ω_e is the electron gyrofrequency, E
 203 is the dimensionless particle kinetic energy, $\beta = [E(E + 2)]^{1/2}/(E + 1)$, R is the ratio of the
 204 relative wave power, x_j and y_j are the wave frequencies and wave numbers which are the resonant
 205 roots for the wave found from the plasma dispersion relation, δx and x_m are also found from these
 206 roots, and j is the number of roots. See Summers et al., (2007) for a full discussion of this equation.
 207 The solution of the minimum resonant energy of an electron with an EMIC wave (equation 2)
 208 depends on the solution of a plasma dispersion relation, which is a function of the local ion
 209 composition, number density, and magnetic field. The diffusion coefficient (equation 3) also
 210 depends on these parameters, as well as the relative power of the wave to the background magnetic
 211 field, and the assumed Gaussian spectral density of the wave power.
 212

213 To compute the minimum resonant energy and diffusion coefficients for EMIC waves of
 214 interest in this study we use the Full Diffusion Code (Ni et al., 2008, 2011; Shprits and Ni et al.,
 215 2009). This model calculates minimum resonant energies and diffusion coefficients for input wave
 216 parameters based on wave-particle interaction theory described above. With the modeled diffusion
 217 coefficients, a one-dimensional pure pitch-angle diffusion equation (e.g., Ni et al., 2015) is solved
 218 numerically to simulate the time-evolution of electron phase space density:

$$\frac{\partial f}{\partial t} = \frac{1}{T(\alpha_{eq}) \sin(2\alpha_{eq})} \frac{\partial}{\partial \alpha_{eq}} \left[T(\alpha_{eq}) \sin(2\alpha_{eq}) \langle D_{\alpha\alpha} \rangle \frac{\partial f}{\partial \alpha_{eq}} \right] \quad (4)$$

220 where f is phase space density, t is time, α_{eq} is equatorial pitch angle, $\langle D_{\alpha\alpha} \rangle$ is the bounce-
 221 averaged pitch angle diffusion coefficient, and the normalized electron bounce period $T(\alpha_{eq}) =$
 222 $1.3802 - 0.3198[\sin(\alpha_{eq}) + \sqrt{\sin(\alpha_{eq})}]$ (Lenchek et al., 1961).

223 **3. 8 June 2015 Event Study**

224 Hogan et al., (2021) reported daily-averaged PSD between 26 March – 20 June 2015 and
 225 showed the development of a local minimum in PSD near $L^* = 3.5$. During this period the time of
 226 greatest deepening of the observed minimum was during a moderate geomagnetic storm on 8 June
 227 2015, where the Dst_{min} reached -67 nT. Panel a of Figure 1 shows the Dst during this event and
 228 vertical-colored lines denote times where the satellite observes multi-MeV electrons at $K = 0.10$

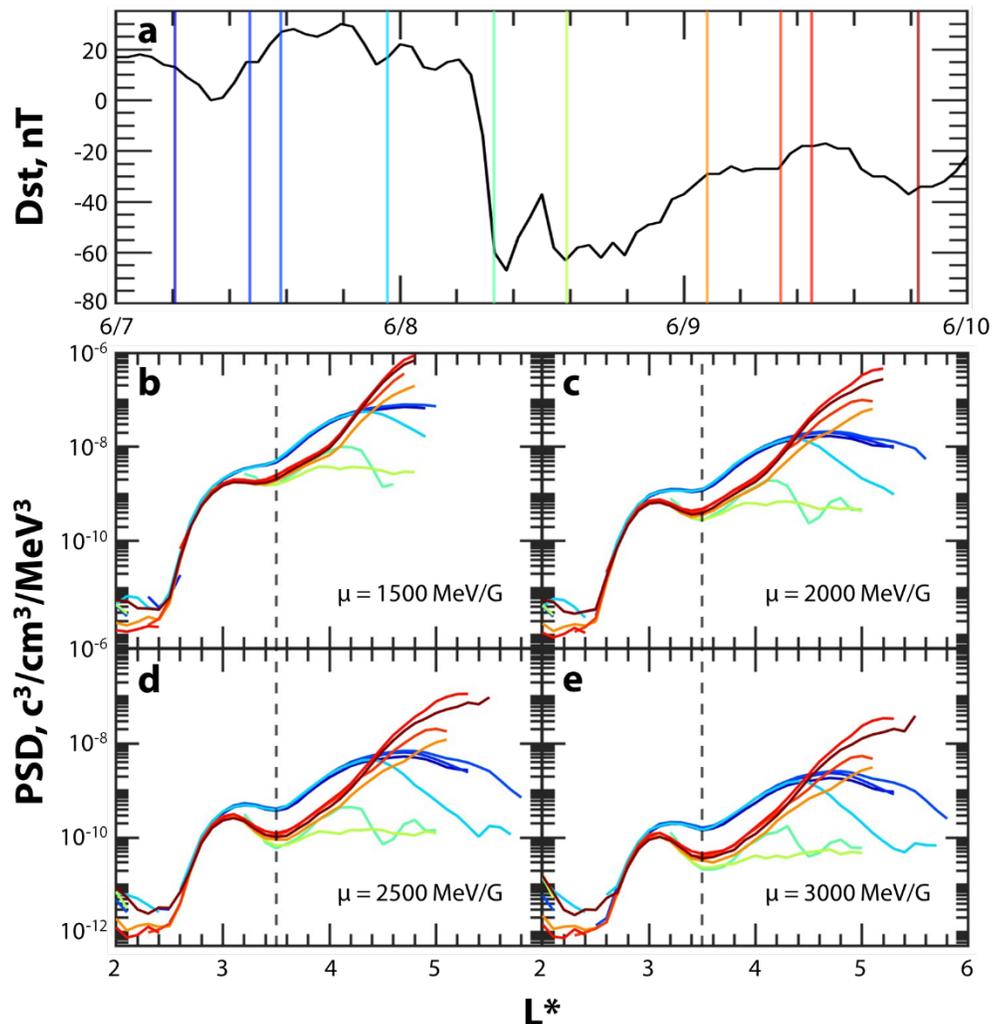


Figure 1. Panel A: Dst for 7-9 June 2015. Vertical lines indicate passes where Van Allen Probe A observes multi-MeV electrons at $L^* = 3.5$, $K = 0.10 G^{1/2}R_E$. Panels b – e show pass averaged radial PSD profiles for $K = 0.10 G^{1/2}R_E$ and $\mu = 1500, 2000, 2500,$ and 3000 MeV/G respectively. The colors of the radial profiles correspond to the times shown for the same-colored lines in panel a. A vertical dashed line at $L^* = 3.5$ is shown in panels b – e.

229 $G^{1/2}R_E$ and $L^* = 3.5$ for 7 through 9 June 2015. These vertical lines are plotted at the center time
230 of each of these observation bins from each satellite pass. Panels b through e show radial profiles
231 of PSD during this period, averaged for each of these observation bins from satellite passes. The
232 color of each profile corresponds to the passes indicated in panel a. PSD is calculated for diagnostic
233 first adiabatic invariant values $\mu = 1500, 2000, 2500,$ and 3000 MeV/G, second adiabatic invariant
234 value $K = 0.10 G^{1/2}R_E$, and L^* bins ± 0.05 . This value of K is selected as the lowest value at which
235 multi-MeV electrons are nearly continuously observed by the Van Allen Probes mission. These
236 narrow L^* bins provide 21-28 data points per observation bin at $L^* = 3.5$. The selected invariant
237 values roughly correspond to 3.4, 4, 4.5, and 5.0 MeV electrons at $L^* = 3.5$. Panel e shows that
238 both inbound and outbound satellite passes of 3000 MeV/G electrons decrease by a factor of 6.8
239 within one satellite orbit near $L^* = 3.5$ during this event, forming a local minimum in one satellite
240 orbit. The loss is energy dependent, as seen by the increasing prominence of the minimum shown
241 in panels B through D with increasing μ . Decreases by factors of 3.3, 4.5, 6.5, and 6.8 are shown
242 for the 1500, 2000, 2500, 3000 MeV/G populations. Results here are shown from Van Allen Probe
243 A. Results from Probe B for the same period are shown in the Supporting Information, and show
244 the same local minimum at $L^* = 3.5$ with similar decrease in one orbit, with a slight time shift due
245 to the trailing Probe B passing the $L^* = 3.5$ region ~one hour after Probe A. A comparison of PSD
246 at $L^* = 3.5$ from both spacecraft is also shown in the Supporting Information. We also note a slight
247 variation in the precise L^* location of the local minimum when found with fine L^* bins 0.1 wide:
248 at $L^* = 3.4, 3.5,$ and $3.5-3.6$ for the 2000, 2500, and 3000 MeV/G electron populations. A local
249 minimum also exists in PSD near $L^* = 4.5$ during one satellite pass near the storm main phase,
250 however this feature could be adiabatic as it does not exist in subsequent satellite passes, and

251 perhaps is a function of the magnetic field model not accurately representing realistic L^* values at
 252 high L^* where the magnetic field can become more dynamic during the main phase of the storm.

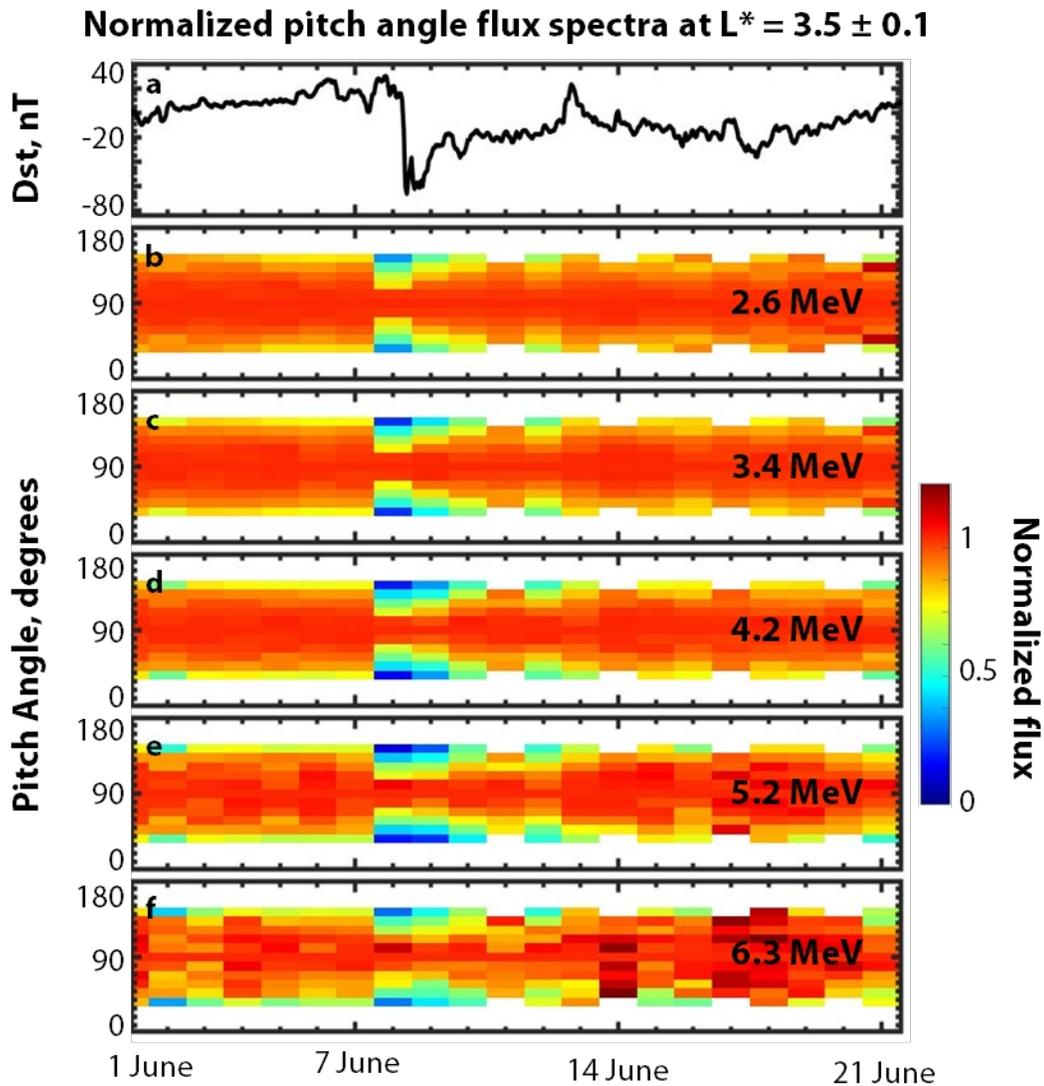


Figure 2 Dst, and daily-averaged normalized flux spectra from the 2.6 – 6.3 MeV energy channels from REPT for 1 – 21 June 2015. Data is from Van Allen Probe A. Normalized flux spectra are found by normalizing the pitch angle flux spectra to the 90-degree flux measurements.

253 Figure 2 shows the Dst in panel a and normalized flux spectra in panels b through f for the
 254 first three weeks of June 2015. The daily-averaged local flux spectra at $L^* = 3.5$ are normalized in
 255 pitch angle to the 90-degree flux measurements to show the representative shape of the spectra (as
 256 in Aseev et al., 2017; Usanova et al., 2014). These measurements show that the pitch angle

257 distribution of multi-MeV electrons is a common broad pancake distribution (e.g., Roederer 1970)
258 in the pre-storm conditions of the event. On 8 June 2015 we show the presence of narrowing of
259 the normalized-pitch angle spectra via strong losses in the normalized spectra at low-pitch angles
260 relative to near-90° trapped particles, referred to as pitch angle bite outs (e.g., Bingley et al., 2019;
261 Usanova et al., 2014). The pitch angle spectra then recover after the event to a broad pancake
262 spectrum by 13 June for the remainder of the period shown. These bite-outs are shown in energies
263 up to the 6.3 MeV energy channel measurements from REPT.

264 The wave power spectral density during 0 – 6 UT 8 June 2015 is shown in Figure 3 and is
265 analyzed for signatures of EMIC waves. He⁺ and O⁺ gyrofrequencies are plotted and labeled in
266 purple and are calculated using the magnitude of the measured magnetic field at the spacecraft.
267 The H⁺ gyrofrequency is greater than those shown here, however, no relevant features are present
268 in the wave power spectral density at these higher frequencies, therefore we focus on features in
269 wave power at <5 Hz in Figure 3. We note the regions of contamination in these measurements in
270 Figure 3. The constant power through the ion gyrofrequencies and constant vertical bands of wave
271 power spectral density near 1:30-2:30 UT is likely instrument contamination as wave power will
272 generally exhibit cutoffs near the gyrofrequencies due to the dampening effects of the actual ion-
273 electron interactions (e.g., Fraser, 1985). Analysis is also conducted to find wave normal angle and
274 ellipticity. These calculated parameters from the magnetometer data are analyzed for signatures of
275 EMIC waves: wave power one order of magnitude greater than the average power in a frequency
276 bin over the time range of study, wave normal angles <30 degrees, and ellipticity close to -1

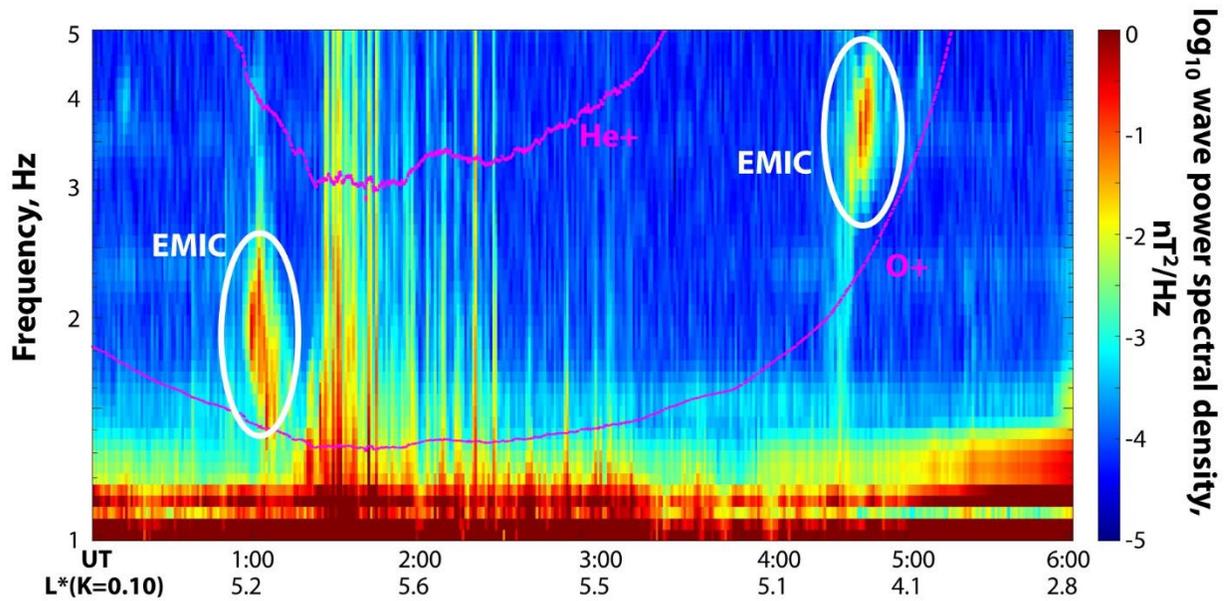


Figure 3 Wave power spectral density for 0-6 UT 8 June 2015. Data is from Van Allen Probe A. He⁺ and O⁺ ion gyrofrequencies are plotted in purple using the measured magnetic field from the EMFISIS instrument. Regions of EMIC power are identified and labeled. L* values corresponding to $K = 0.10 G^{1/2}R_E$ at each hour are reported below the x-axis.

277 indicating left hand polarized waves, matching EMIC wave theory and results from statistical
 278 studies of EMIC wave observations (Cao et al., 2020; Chen et al., 2019; Saikin et al., 2015).
 279 Regions in which these criteria for EMIC waves are satisfied are circled in Figure 3. Near 1:00 UT
 280 and 4:45 UT there are signatures of EMIC waves shown in the He⁺ band just above the O⁺
 281 frequency, characteristic of where bursts of wave power are commonly observed relative to the
 282 local ion gyrofrequencies (e.g., Usanova et al., 2021). We note here this observation of EMIC
 283 waves occurs near $L^* = 4.2 - 4.3$, higher than where the observation of rapid loss is shown near
 284 $L^* = 3.5$. Similar analysis from RBSP B does not show any EMIC wave signatures during 7-8
 285 June 2015.

286 The results in Figure 1 indicate a loss process that is energy dependent with loss which
 287 increases with μ and occurs on timescales within one 9-hour satellite orbit. The results in Figure 2
 288 show accompanying pitch angle bite outs with these observations. The local number density is also

289 analyzed as found from EMFISIS data and indicates local number density $\sim 960 \text{ cm}^{-3}$ at $L^* = 3.5$
290 during the satellite pass of interest, indicating that the satellite is in a region of dense plasma and
291 likely within the plasmopause, normally indicated by number densities $> 100 \text{ cm}^{-3}$. Local number
292 density has also been used to identify the plasmopause crossings during the Van Allen Probes era
293 by the EMFISIS data team. These results show that the spacecraft is within the plasmasphere
294 during this loss event. The local number density and plasmopause crossing locations found from
295 the local number density are shown in the Supporting Information. Plasmopause crossings of L^*
296 $= 4.6$ are indicated in the orbit preceding the observed loss, and compression of the plasmopause
297 to $L^* = 3.9$ is indicated during the pass where rapid PSD loss is first observed. Thus, the observed
298 feature at $L^* = 3.5$ occurs well within the plasmopause boundary. Chorus waves do not propagate
299 well within the dense plasmopause (e.g., Meredith et al., 2001). Hiss waves can occur within the
300 plasmopause but have not been shown to strongly affect MeV electrons on these timescales (e.g.,
301 Malaspina et al., 2016; Selesnick et al., 2003; Thorne et al., 2013). Rather, hiss waves
302 preferentially affect 100s of keV electrons (e.g., Ni et al., 2019; Zhao et al., 2019), much lower than
303 the $> \text{MeV}$ populations affected here. Therefore, neither chorus nor hiss wave-particle interactions
304 are likely to a prominent driver of multi-MeV electron dynamics during this event at $L^* = 3.5$.
305 PSD increases at higher L^* values, suggesting no readily apparent effects of magnetopause
306 shadowing on the trapped particle populations at $L^* = 3.5$. The loss feature is shown to persist in
307 pass-averaged PSD through the ~ 2 -day period after the initial loss observation shown, and the
308 resulting local minimum in PSD exists until a strong storm on 21-23 June 2015 in daily-averaged
309 PSD (Hogan et al., 2021). The persistence of this feature with Dst recovery indicates that the
310 process is not adiabatic and the Dst effect is not causing these dynamics. Furthermore, radial
311 diffusion should oppose the formation of PSD gradients and local extrema such as reported here,

312 thus the process occurring exceeds the effects of radial diffusion. EMIC waves are the most likely
313 driving mechanism as their effects are strong within the plasmopause, preferentially affect
314 electrons of increasing energies (specifically in the >MeV range), cause loss on rapid timescales,
315 are shown to cause rapid-forming pitch angle bite outs and are shown to contribute to the formation
316 of similar minimums in PSD at higher- L^* values. EMIC waves are also observed during the
317 satellite orbit where the rapid loss is shown, however at higher L^* values. Therefore, due to the
318 lack of likely contributions from other established drivers of multi-MeV electron loss, EMIC wave
319 effects arise as the most likely mechanism to contribute to this PSD minimum at $L^* = 3.5$. We here
320 quantify the effects of EMIC waves on the PSD population observed using wave-particle
321 interaction theory.

322 **4. PSD simulations and comparisons with observations**

323 We calculate minimum resonant energies and diffusion coefficients from EMIC waves
324 using quasi-linear theory to estimate the timescale of loss due to these waves. These values are
325 found using the full diffusion code (Ni et al., 2008, 2011; Shprits and Ni et al., 2009) which solves
326 equations (2), (3), and the solution of a cold plasma dispersion relation. Input parameters are
327 derived from spacecraft measurements when possible. Electron number density is 960 cm^{-3} as
328 derived from EMFISIS measurements. Wave shape is found from a Gaussian fit of the form
329 $\exp(-[f - f_m]/\delta f)^2$ to the time-averaged power near 4:45 UT which fulfills EMIC wave criteria
330 with the parameters $f_m = 0.57 \text{ Hz}$ and $\delta f = 0.045 \text{ Hz}$ (shown in the Supporting Information). The
331 local equatorial magnetic field strength is found to be 647 nT from EMFISIS measurements. The
332 local plasma composition is taken to be 70% H+, 20% He+, and 10% O+ as found by Meredith et
333 al., (2003) and as used for similar diffusion coefficient calculations (e.g., Summers & Thorne,
334 2003; Usanova et al., 2014). The EMIC waves are assumed to be confined within $\pm 15^\circ$ as

335 consistent with observations of other EMIC wave events (Chen et al., 2019, Saikin et al., 2015).
336 The wave normal angle is assumed to have a quasi-parallel distribution (e.g., Ni et al., 2015). The
337 effects of polarization reversal are not considered here (e.g., Cao et al., 2020). We here consider
338 orders of cyclotron resonance from -5 to 5. The EMIC waves are assumed to be left-hand polarized
339 as considered for prior EMIC wave diffusion coefficient theory (Summers et al., 2007) and as
340 observed for EMIC waves observed at higher L^* values during the event, shown in Figure 3. Two
341 different cases are evaluated for the diffusion coefficients due to EMIC waves at $L^* = 3.5$ in the
342 absence of their direct observation, scaling the frequency of the nearby observed wave power to
343 the time when the spacecraft crosses $L^* = 3.5$ using the local magnetic field strength, or assuming
344 similar waves as those observed at higher L^* values. These two cases are presented in this study:
345 First, we consider He⁺ band EMIC waves, which are the band in which EMIC wave power is
346 observed during the satellite orbit of loss as shown in Figure 3. The frequency range of the wave
347 spectrum is normalized to the time when the spacecraft passes $L^* = 3.5$ based on measurements of
348 the magnetic field strength during 04:38:40 – 04:49:56 UT. This normalization is done by scaling
349 the central frequency of the wave and the wave power spectral width such that the ratio of these
350 parameters to the He⁺ frequency band are the same as the observations of the nearby EMIC wave
351 power. Second, we normalize the frequency range of the spectrum based on a magnetic field
352 strength of 647 nT. This frequency range of the spectrum is located mainly in the O⁺ band when
353 the spacecraft is in the region near $L^* = 3.5$, thus the waves are treated as O⁺ band EMIC waves
354 with an upper frequency limit of 0.99 times the local O⁺ gyrofrequency. This allows for the
355 consideration and comparison of the effects of He⁺ and O⁺ band EMIC waves during the event
356 with realistic wave parameters as observed during the satellite orbit of interest, as no EMIC waves

357 are directly observed during the spacecraft crossing of $L^* = 3.5$ during which the rapid PSD loss
 358 is observed.

359 The minimum resonant energies and pitch angle diffusion coefficients for each of these
 360 cases are shown in Figure 4. Minimum resonant energies are indicated by the minimum energy at
 361 which the diffusion coefficient is defined at a given pitch angle, the waves do not resonate with
 362 electrons at energies where the diffusion coefficient is not defined. The value of the pitch angle
 363 diffusion coefficient is indicated by the color scale in Figure 4. The calculated energy and cross
 364 diffusion terms are multiple orders of magnitude less than the calculated pitch angle diffusion
 365 coefficients; we will focus only on the effects of pitch angle diffusion here. The dispersion
 366 relationship results, explicit resonant regions, and energy and cross diffusion terms are shown in
 367 the Supporting Information. Panel A shows the results for He⁺ band EMIC waves, and that they
 368 do not resonate with electrons less than 56 MeV at $\alpha_{eq} = 54^\circ$ (which corresponds to $K = 0.10$

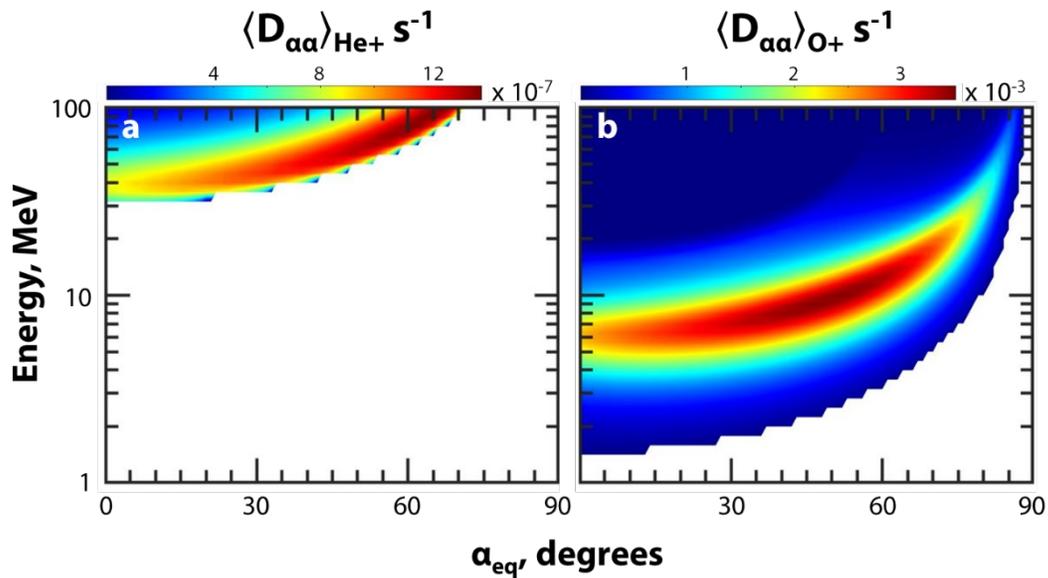


Figure 4 Panel a: minimum resonant energy and bounce-averaged diffusion coefficient calculated for He⁺ band EMIC waves with the described input parameters. Minimum resonant energies are the lowest energy at each pitch angle for which the diffusion coefficient is defined. The strength of the diffusion coefficient is indicated by the color bar on top of the plot. Panel b: Same as left, but for O⁺ band EMIC waves.

369 $G^{1/2}R_E$ at $L^* = 3.5$ during this event), much higher than the energies where loss is observe. In panel
370 b, we show that representative O+ band EMIC waves can resonate with electrons down to 2.8 MeV
371 energies at $\alpha_{eq} = 54^\circ$, encompassing the electron energies observed to decrease during this event
372 of study. The diffusion coefficients due to O+ band waves are also much larger – about 4 orders
373 of magnitude greater when comparing peak values in the energy ranges presented here. We also
374 show in Figure 4 that the diffusion coefficient increases with increasing electron energy from
375 \sim MeV to several MeV, which matches the behavior of the loss mechanism observed and shown in
376 Figure 1.

377 To model the effects of these diffusion coefficients on electron PSD we use a one-
378 dimensional pitch angle diffusion model (equation 4) (e.g., Ni et al., 2015). Boundary conditions
379 for modeled PSD f are $df/dt(\alpha_{eq} = 90^\circ) = 0$ and $f(\alpha_{eq} < \alpha_{loss\ cone}) = 0$. The first condition
380 is an upper boundary condition stating that there should not be any change in PSD for particles
381 that are perfectly trapped, and the second condition defines that PSD within the loss cone should
382 exhibit rapid loss during the simulation. We assume the initial PSD profile follows a sine function
383 in equatorial pitch angle (e.g., Ni et al., 2013, 2015). We match the prescription of initial PSD to
384 the PSD observations from RBSP A shown in Figure 1, noting that the observations shown in
385 Figure 1 are for second adiabatic invariant $K = 0.10 G^{1/2}R_E$ which corresponds to $\alpha_{eq} = 54^\circ$ at L^*
386 $= 3.5$ during this event. PSD evolution is simulated by solving equation (1) over one 9-hour
387 satellite orbit and shown in Figure 5 for the 3000 MeV/G population, which corresponds to \sim 5
388 MeV electrons at $L^* = 3.5$ and $K = 0.10 G^{1/2}R_E$. We assume EMIC waves are present for 2% of

PSD simulation and observations at $L^* = 3.5$
 $\mu = 3000 \text{ MeV/G}$, $K = 0.10 \text{ G}^{1/2}R_E$

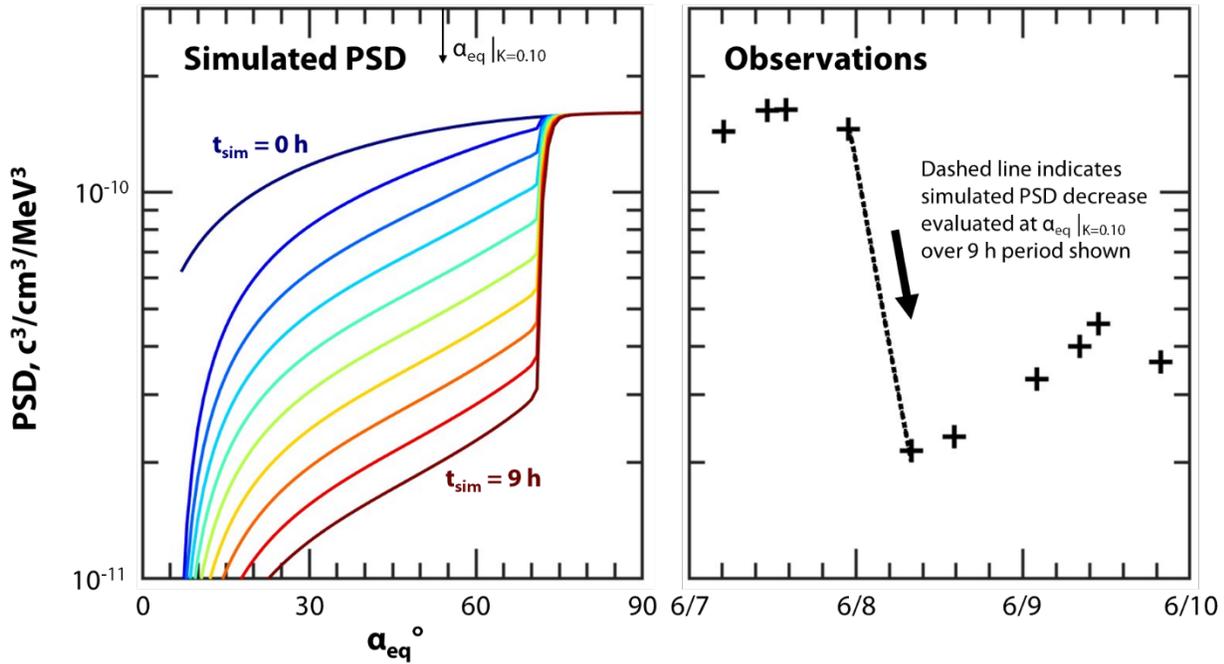


Figure 5 Left: simulated PSD for $\mu = 3000 \text{ MeV/G}$, $K = 0.10 \text{ G}^{1/2}R_E$ electrons using the pure pitch angle diffusion model described in the text. The pitch angle corresponding to $K = 0.10 \text{ G}^{1/2}R_E$ is indicated on the top x-axis, and the initial PSD value at this pitch angle is prescribed to match the observed PSD by Van Allen Probe A immediately before the observed loss at $L^* = 3.5$. The evolution of PSD is plotted every hour and progresses from blue to red for 9-hours. Right: Pass-averaged PSD from Van Allen Probe A for $\mu = 3000 \text{ MeV/G}$, $K = 0.10 \text{ G}^{1/2}R_E$ electrons at $L^* = 3.5$ plotted with + marks for 7 through 9 June 2015. Simulated PSD (shown on the left) is evaluated at the pitch angle corresponding to $K = 0.10 \text{ G}^{1/2}R_E$ and shown with a dashed line, starting from the satellite pass point used for initial conditions for the PSD simulation.

389 the drift orbit of the electrons, similar to MLT drift orbit averaging assumed by other studies (e.g.,
 390 Summers et al., 2007) and agreeing with the occurrence rate ranges of O+ band EMIC waves at
 391 $L^* = 3.5$ (Chen et al., 2019; Saikin et al., 2015). These simulation results are shown in the left
 392 panel of Figure 5. The initial spectrum of PSD is shown in blue, for we prescribe such that the
 393 PSD at $\alpha_{eq} = 54^\circ$ agrees with the observations from Van Allen Probe A from the pass immediately
 394 before the rapid decrease in PSD. We plot PSD spectra progression every hour with color
 395 progressing from red to blue. Results in Figure 5 are for $\mu = 3000 \text{ MeV/G}$ electrons over 9-hours,

396 which is one satellite orbit, the amount of time during which Van Allen Probe A observes rapid
397 PSD loss. This simulation result in Figure 5 shows the significant and fast decrease in PSD at
398 $\alpha_{eq} \lesssim 70^\circ$, and the narrowing of the pitch angle spectra over the course of the satellite orbit
399 simulated. In the right panel of Figure 5, we compare this simulation result (dashed line) with the
400 observed PSD from Van Allen Probe A from 7 through 9 June 2015. Observed PSD at $L^* = 3.5$,
401 $K = 0.10 G^{1/2}R_E$ is shown for each satellite pass and indicated by + marks. Evaluating the
402 simulation result at $\alpha_{eq} = 54^\circ$, we show here good agreement between the simulated PSD loss due
403 to EMIC wave effects and the observations, under the simulation conditions and diffusion
404 coefficients found as described.

405 Results shown in Figure 5 are for 3000 MeV/G electrons and show a decrease by a factor
406 of 7.2, compared to observational decrease of 6.8 over a 9-hour period. Similar analysis is done
407 for the 1500, 2000, and 2500 MeV/G populations, for which we report respective decreases by
408 factors of 2.8, (3.2 observed), 3.6 (4.5 observed), 5.0, (6.5 observed), 7.2 (6.8 observed) for these
409 populations over the 9-hour period. These results for all μ values are shown in the Supporting
410 Information.

411 **5. Discussion**

412 The calculation of diffusion coefficients for representative EMIC waves during the event
413 as shown in Figure 4 indicates that EMIC waves in the O⁺ band and not the He⁺ band can be
414 driving the loss of electrons at multi-MeV energies as shown in Figure 1. We modeled PSD
415 evolution using these EMIC wave effects and pure pitch angle diffusion. The results in Figure 5
416 show decrease of PSD at lower pitch angles while preserving the populations at higher pitch angles,
417 thus narrowing the pitch angle spectra, as observed during the event and shown in Figure 5. O⁺

418 band EMIC waves are less common than He⁺ band EMIC waves as found by studies of EMIC
419 observations from the Van Allen Probes era (Sigsbee et al., 2023, Chen et al., 2019, Yu et al.,
420 2015); however, when O⁺ EMIC waves are observed, they are most prevalent in the range $3 < L$
421 < 4 , which is the region where this loss is observed, and are as common as H⁺ EMIC waves in this
422 region (Chen et al., 2019; Saikin et al., 2015). The dwell time of the spacecraft decreases with L
423 value (as shown by Chen et al., 2019; Sigsbee et al., 2023; Yu et al., 2015) decreasing the
424 likelihood of observing EMIC wave structures in this region. Studies by Yu et al., (2015) of the
425 early Van Allen Probes era (2012-2014) suggest that O⁺ EMIC waves are found generally in the
426 outer plasmasphere and occasionally the plasma trough which is the region in which this loss
427 process is observed. In this region the O⁺ density can be higher than the partial ion compositions
428 used here, thus increasing the strength of O⁺ band EMIC waves. A study of Van Allen Probes data
429 from 2012-2017 by Chen et al., (2019) shows that O⁺ band waves do occur mostly in the region
430 3-3.5 R_E , which corresponds to this region of loss. This study also showed that O⁺ band EMIC
431 waves are observed to have small wave normal angles and linear polarization as assumed here.
432 EMIC waves can be bursty and occur on short timescales making them difficult to be fully
433 measured in time and space even by a two-spacecraft mission, but EMIC effects can be observed
434 in these multi-MeV electrons which have drift periods on the timescale of minutes and transport
435 information about the waves to the satellite for measurement. O⁺ band waves specifically are
436 thought to happen near the plasmopause boundary where the oxygen torus (e.g., Nose et al., 2015)
437 expands and leads to growth of O⁺ band waves in this region (Yu et al., 2015). During the event
438 of study, no appreciable O⁺ density increase was shown using partial ion densities as found from
439 the Helium, Oxygen, Proton, and Electron (HOPE) instrument, or from inferred ion densities down

440 to $>eV$ energies using the methods of Goldstein et al., (2013), as shown in the Supporting
441 Information. Therefore, it is not clear that the oxygen torus is present during this event.

442 Minimum resonant energies and the strength of diffusion coefficients from EMIC wave
443 effects will vary due to the temperature of the ions and the local ion composition, as seen in
444 equations (1) and (2). Here, we have assumed a cold plasma, and the solution of a cold plasma
445 dispersion relation is used for computing the results of equations (1) and (2) as developed by
446 Summers & Thorne (2003) and Summers et al., (2007). Sensitivity of the solutions of plasma
447 dispersion relations when using cold, warm, or hot plasma dispersion relations have been discussed
448 in previous studies, and have been shown to affect the solution by changing the wave number
449 solution which changes the resonant conditions (e.g., Bashir et al., 2021, 2022; Lee et al., 2014).
450 However, these observations and modeling in this study are made at low L^* values where the local
451 number density is near 1000 cm^{-3} and within the plasmopause. Therefore, a cold plasma
452 approximation is an accurate assumption for the solutions of (1) and (2). Similar use of the cold
453 plasma dispersion relation has been used for calculating diffusion coefficients for EMIC waves up
454 to $L^* = 4.5$ (Usanova et al., 2014).

455 Ion compositions must also be assumed due to the lack of direct in-situ measurements. In
456 certain events when EMIC waves are observed in multiple bands, one can estimate the local ion
457 compositions (e.g., Min et al., 2015; Qin et al., 2019). However, in the event of study, only one
458 band is shown, and at higher L^* values than where the observed loss feature occurs. Therefore, the
459 local ion composition must be assumed. The solution of the plasma dispersion relation is sensitive
460 to the local ion composition (e.g., Bashir et al., 2021, 2022; Summers et al., 2007). The assumed
461 compositions found by Meredith et al., (2003) however provide adequate representative
462 parameters for the local ion compositions and have been used for similar studies of diffusion

463 coefficients from EMIC waves (e.g., Usanova et al., 2014). Furthermore, the minimum resonant
464 energy does not vary as strongly with ion composition as it does with other parameters (such as
465 local number density, which is inferred from satellite measurements during the event). Significant
466 deviation from statistically found average EMIC wave characteristics and ion compositions would
467 be required for He⁺ band waves to affect the populations where loss is observed, therefore it is
468 more likely here that O⁺ band waves are affecting these multi-MeV electrons at L* = 3.5 than He⁺
469 band waves.

470 Here we have only modeled the effects of L-mode quasi-linear EMIC waves. Other studies
471 acknowledge that often the combined effects of EMIC waves with other waves such as chorus or
472 hiss waves chorus and/or hiss waves are required to produce loss of the entire pitch angle spectra
473 to fully match observations of loss at high α_{eq} (Drozdov et al., 2020; Qin et al., 2019; Ross et al.,
474 2021). We show here that EMIC wave effects can account for the loss in PSD shown and can
475 induce narrowing of the pitch angle spectra, but that other loss mechanisms must be present to
476 affect the dynamics of higher pitch angle electrons, PSD at high pitch angles remain constant in
477 our simulations as shown in Figure 5 due to the lack of a defined pitch angle diffusion coefficient
478 at that region for the electron populations of study. Hiss waves are prevalent within the
479 plasmopause can scatter particles to the pitch angles where they can then be affected by EMIC
480 waves (e.g., Drozdov et al., 2020; Li et al., 2007). The loss feature at L* = 3.5 is shown to be
481 within the plasmopause here as shown here. A study of multi-MeV electron flux data from the Van
482 Allen Probes in 2015 by Ross et al., (2021) suggested that hiss wave and EMIC waves are both
483 required to reproduce observed loss at L* ≤ 3.75. While their study did not include O⁺ band EMIC
484 waves due to their low occurrence rate, we show here that representative O⁺ band waves alone

485 can account for large loss in multi-MeV electron PSD on rapid timescales during the event of
486 study.

487 Other governing factors of the simulation space may be found to affect the L^* dependence
488 of local minimums in PSD. Preconditioning of the system may be important for these structures,
489 as EMIC wave effects are generally most prevalent when the wave first interacts with the dense
490 plasmasphere (e.g., Usanova et al., 2021). Compression of the plasmopause may be necessary for
491 EMIC wave effects to cause local minimums in multi-MeV electrons at lower L^* values, such as
492 during the strong storm in March 2015 before this observation ($D_{st_{min}} = -234$). During the period
493 after the March 2015 storm through June 2015, Hogan et al., (2021) show the development of the
494 local minimum at $L^* = 3.5$ discussed here. During this period and before the 8 June event studied
495 in detail here, other moderate storms in terms of Dst are present: 10-11 April ($D_{st_{min}} = -85$ nT),
496 15-19 April ($D_{st_{min}} = -88$ nT), and 11-13 May ($D_{st_{min}} = -82$ nT). Decay of PSD at $L^* = 3.5$ during
497 these events contributes to local loss but not the formation of a local minimum in PSD, only during
498 the 8 June event is the PSD low enough at $L^* = 3.5$ that a minimum can then form. Loss during
499 these events prior moderate events may have been preferential at $L^* = 3.5$ as well, and perhaps
500 governed by the same mechanisms as those discussed here, as EMIC waves are most effective at
501 causing loss when first crossing the plasmopause, regardless of wave band. While continuous O+
502 band waves are unlikely due to their infrequent observations, it is possible that EMIC waves in the
503 He+ or H+ bands are causing local loss during these prior storms, or other mechanisms not revealed
504 in this event study are present. Hiss waves also affect multi-MeV electrons on these multi-month
505 timescales and may play a part in the preconditioning of PSD at $L^* = 3.5$ for the 8 June 2015 event
506 as well. This topic warrants future research as the loss at certain L^* values can lead to the formation
507 of the third radiation belt and significantly affect dynamics of the radiation belt structure, and here,

508 driving mechanisms of uncommon wave types (O+ band EMIC waves) are shown to be able to be
509 capable of causing this feature during only a moderate geomagnetic storm in terms of Dst ($D_{\text{st}_{\text{min}}}$
510 = -67 nT) under the given preconditioning. Therefore, future study is required.

511 **6. Conclusions**

- 512 1. Rapid loss of multi-MeV electron PSD is shown during a moderate storm with
513 minimum Dst = -67 nT. This loss is primarily at $L^* = 3.5$ and causes a local PSD
514 minimum to form within one satellite orbit. The loss is shown to be energy dependent,
515 with increasing prominence of the local minimum with increasing μ .
- 516 2. Pitch angle bite outs are shown in multi-MeV electron flux channels from the REPT
517 instrument during this event, indicating narrowing of the pitch angle distribution and a
518 loss mechanism that affects multi-MeV electrons most strongly at lower pitch angles.
- 519 3. Quasi-linear theory is used to analyze the effects of He+ and O+ band waves for the
520 plasma environment at $L^* = 3.5$ during the event. Analysis of minimum resonant
521 energies due to each wave type show O+ band waves as a possible driver of multi-MeV
522 electron dynamics. Representative O+ band EMIC wave effects are simulated in a one-
523 dimensional pitch angle diffusion model of PSD using initial conditions observed
524 during the event and calculated diffusion coefficients. These simulation results show
525 that O+ band EMIC waves can produce loss rates similar to the observed multi-MeV
526 PSD loss at $L^* = 3.5$ in one satellite orbit.

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535 [ect.newmexicoconsortium.org/data_pub/](https://rbsp-ect.newmexicoconsortium.org/data_pub/). EMFISIS data are is available from the NASA OMNI
536 web database: <https://omniweb.gsfc.nasa.gov/>. Plasmopause location determined from local
537 number density measurements by Craig Kletzing is available at
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