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Scattering by whistler-mode waves during a quiet period perturbed by substorm activity

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1 **Scattering by whistler-mode waves during a quiet period perturbed by substorm**
2 **activity**

3

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52 **Abstract (150):**

53

54 We study the dynamics of radiation belt electrons during a 10-day quiet period
55 perturbed by substorm activity and preceding a high-speed stream (HSS), aiming at a
56 global description of the radiation belts in L-shell, L in [2, 6], and energy [0.1, 10] MeV.
57 We combine Van Allen Probes observations and Fokker-Planck numerical simulations of
58 pitch-angle diffusion. The Fokker-Planck model uses event-driven pitch angle diffusion
59 coefficients from whistler-mode waves, built from the wave properties and the ambient
60 plasma density measurements from the Van Allen Probes. We first find this event has
61 some similar characteristics to regular quiet times previously studied; a widely
62 extended plasmasphere within which we observe strong and varying whistler-mode
63 waves. These ambient conditions lead to strong pitch-angle scattering, which
64 contributes to the creation of a wide slot region as well as a significant decay of the outer
65 radiation belts, which are observed and qualitatively well simulated. In addition, we find
66 the substorm activity causes short duration (within +/- 4h) decay of the plasma density
67 and a lowering amplitude of the whistler-mode waves within the plasmasphere, both
68 causing opposite effects in terms of pitch angle diffusion. This leads to a diminution of
69 pitch-angle diffusion at the time of the main substorm activity. Conversely, whistler-
70 mode waves become enhanced in the time periods between the substorm injections. All
71 effects cumulated, we find an enhancement of pitch angle diffusion by whistler-mode
72 waves above $L \sim 4.7$ during the 10-day period. This directly relates to the combination of
73 quietness and substorm activity which allows pitch angle diffusing of up to 1 MeV
74 electrons in the outer belt. Relativistic electrons of 1 to 2 MeV remain trapped in the

75 outer belt, from $L \sim 4.7$ to $L \sim 5.2$, forming, in both the observations and the simulations, a
76 distinct pocket of remnant electrons.

77

78 **Keywords:**

79 Electron, wave-particle interactions, radiation belts, moderate substorm activity,

80 substorm, whistler waves.

81

82 **1. Introduction**

83

84 Earth's electron radiation belts consist of two toroidal belts of energetic charged
85 particles (~ 0.1 to ~ 10 MeV) surrounding Earth, with the inner belt sitting between 1
86 and 3 Earth radii (R_E) and the outer belt typically lying between 3 and 7 R_E in the
87 equatorial plane. Between the two radiation belts lies a zone often devoid of electrons,
88 called the slot region. This ideal representation is highly dynamic in both space and
89 time; first, because dynamic/disturbed conditions bring complex dynamic mono- (e.g.
90 Reeves et al., 2013) or multi-belt structures (e.g., Baker et al., 2013) and, second,
91 because Earth's radiation belt location is energy dependent (e.g. Lyons and Thorne,
92 1973). In this work, we specifically address the energy dependence of the radiation
93 belts, between 2 and 6 R_E in the equatorial plane, during a period of quiet state
94 perturbed by substorm activity (e.g. Friedel et al., 1996; Turner et al., 2015) and
95 preceding a high-speed solar wind-stream (HSS) (Denton et al., 2017). We focus on the
96 characterization of the fast slot formation and the outer belt decay, which leads to a
97 drastic reduction in the flux level of the whole radiation belt system (e.g. Reeves et al.,
98 2016; Ripoll et al., 2016a). Understanding the variability of the electron radiation belts,
99 to the point of predictability, is one of the great outstanding challenges in space weather
100 research (cf. review in Ripoll et al., (2020) and references therein). All progress made
101 will converge toward new advances in the hardening of electronic spacecraft systems
102 and their protection from severe space weather conditions.

103 This study is based on the analysis of high-quality electron flux observations from
104 NASA's Van Allen Probes (Mauk et al., 2013). Data analysis is supported by
105 computations made with the CEVA code (e.g. Reveillé et al., 2002) that is based on the
106 quasi-linear Fokker-Planck formalism. We feed the CEVA code with event-specific pitch-

107 angle diffusion coefficients (Ripoll et al., 2016a, 2017, 2019a, 2019b) that are computed
108 from in-situ measurements of plasmaspheric hiss waves and the plasma density
109 observations made by the Van Allen Probes. This computational step requires massively
110 parallel computations in order to perform the computation of diffusion coefficients at
111 each satellite outbound pass at time, t , and location, L , i.e. $D_{\alpha_0\alpha_0}(w_i(t, L), n_e(t, L), E, \alpha_0)$,
112 knowing the various locally measured wave properties, generically denoted here
113 $w_i(t, L)$ for $i=1\dots 4$, and the plasma density, $n_e(t, L)$, for any electron of energy, E , and
114 equatorial pitch angle, α_0 . An alternative methodology is the computation of a single
115 diffusion coefficient from statistical mean properties, $D_{\alpha_0\alpha_0}(\widehat{w}_i, \widehat{n}_e, L, E, \alpha_0)$ (with $\widehat{(\cdot)}$
116 denoting a temporal average) which has low numerical cost but neglects correlations
117 between the properties of the ambient domain and, therefore, introduces some error.
118 This method is applied, for instance, to study hiss waves effects in Ma et al. (2016). Our
119 effort of keeping the plasma/wave coupling is motivated by the will to reach the
120 maximum accuracy possible, though approximations always remain (cf. discussion in
121 section 4). This event-driven method has proven successful for an event of 10 days
122 during a quiet period of March 2013 (Ripoll et al., 2016a, 2017, 2019a, 2019b). The new
123 questions we address herein are: can this event-driven method be successful when
124 applied to another, more complex and dynamic, event? How does substorm activity
125 affect the results, their accuracy, and the method?

126 Section 2 of the article describes the event chosen for this study, including the
127 presentation of both the whistler-mode waves and the plasmasphere activity. In Section
128 3 we discuss the numerical method used to compute the event-specific pitch-angle
129 diffusion coefficients. Section 4 shows and discusses NASA's Van Allen Probes flux
130 observations and the quasi-linear simulations of the scattering associated to the
131 whistler-mode wave activity that sustains our analysis. We explain that the moderate

132 substorm activity contributes to decreasing plasmaspheric density, which, in turn,
133 enhances pitch angle diffusion from whistler-mode waves. However, this effect is found
134 insufficient to compensate for the lowering of whistler-mode wave amplitudes that
135 occurs simultaneously. There is nevertheless an enhancement of the mean scattering
136 above $L \sim 4.7$ for electrons up to 1 MeV. This is attributed to the strengthening hiss
137 activity which occurs in between the substorm injections.

138

139 **2. Case analysis: 30 of June 2014 - 10 of July 2014**

140 In this study, we examine the evolution of the radiation belts during a 10-day
141 period in 2014, from 30 June to 10 July. This period corresponds to a period of *calm-to-*
142 *storm* geomagnetic conditions, for which the upcoming storm at the end of the event is
143 driven by high-speed solar wind-streams (HSSs). This event was selected in Denton et al.
144 (2017) who studied the evolution of the ions composition during a 10 day interval
145 preceding the HSS and the HSS itself. High-speed solar wind-streams are well described
146 in Borovsky & Denton (2009, 2010, 2016), Denton & Borovsky (2012, 2017) and Denton
147 et al. (2016) and Hartley et al., 2013 and references therein. This type of event leads to
148 the injection of fresh plasma into the inner magnetosphere, via geosynchronous orbit
149 (GEO), (Friedel et al., 2001; Korth et al., 1999) within a few hours of HSS arrival at the
150 magnetopause (Denton & Borovsky, 2009). In our study, we will focus on the whole
151 period that is reasonably quiet but perturbed by moderate substorm activity. On July 9
152 activity picked up with the HSS and the analysis stops on July 10.

153

154 2.2 Substorm activity

155 Figure 1 contains plots of the geomagnetic conditions, including AE (top) and Kp
156 (bottom) geomagnetic indices. The AE index is well-correlated with the occurrence of

157 substorms—events that are known to inject plasma into the inner magnetosphere,
158 either in isolation or during multiple substorm onsets (Mauk and McIlwain 1974;
159 Reeves et al., 1991; Sergeev et al., 1998; Henderson, Reeves, et al., 2006; Henderson,
160 Skoug, et al., 2006; Turner et al., 2015). During this time period, the AE index remains
161 mostly at very low levels, except for two excursions indicative of substorms (June 30
162 and July 3-4). The Kp index (plotted here as a mean value every 8h) and SYM/H index
163 (Figure 1, 4th image) were also at very low levels. The maximum Kp was reached twice
164 on June 30 and July 10 ($K_p = 3$), and the minimum SYM/H occurred on July 3 (SYM/H=
165 20 nT). Apart from these excursions, both indices highlight the very low levels of
166 magnetospheric activity ($K_p \leq 2$ and SYM/H ~ 0) during this interval.

167 The substorm activity during this time is more complex than it appears from the
168 AE index and Van Allen Probes. There are a number of substorms (and injections) that
169 can be seen from the electron flux reported from 6 satellites of the LANL GEO
170 constellation in Figure 2. Comparison with Van Allen Probes flux is also provided in the
171 2 bottom panels. Van Allen Probes apogee MLT was ~ 9 on July 1. Days of quietness with
172 steady flux are July 1, 5, 6. Small injections occur on July 2 near 12:00 while Probe A was
173 at perigee and Probe B was at very low L and on July 4 while both Probes are in the
174 inner zone. These two injections appear to be single injection followed by drift echoes.
175 July 3 has a longer interval of substorm activity observed both by LANL satellites at GEO
176 and by Van Allen Probes. At the beginning of July 7, we observe another injection that is
177 fairly typical of an isolated substorm, followed by drift echoes. This injection is also
178 visible in the Van Allen Probes data that are located at higher L-shell. Some of these
179 substorms affect the plasmopause location more than others. Substorm injections on
180 July 3 and 7 modify the density and the wave activity as shown in the next subsection.
181 There is also activity on July 8 which perturbation on the density is conversely quite

182 mild and not well apparent (cf. next section and Figure 3). July 9 has two more isolated
183 substorms when Van Allen Probes were at low L. These substorms did seem to move the
184 plasmopause inward as well. The HSS event starts on July 10 with the beginning of the
185 flux enhancements visible in Figure 2.

186

187 2.2 Plasma density

188 NASA's Van Allen Probes consist of twin spacecraft on near-equatorial elliptical
189 orbits. The orbital period is ~ 9 hr, the MLAT coverage $|\text{MLAT}| < 20^\circ$, and the orbital
190 apogee is $\approx 6 R_E$. Full precession of the apogee through all MLTs occurs approximately
191 every 2 years. In this work, we use the data from two waves instruments, the Electric
192 and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) (Kletzing et al.,
193 2013) and the Electric Fields and Waves (EFW) instrument (Wygant et al., 2013), as well
194 as data from the Magnetic Electron and Ion Spectrometer (MagEIS) particle instrument
195 (Blake et al., 2013), all onboard the Van Allen Probes (Mauk et al., 2013).

196 The plasma density enters directly in the dispersion relation that controls the
197 strength of wave-particle interactions. An accurate knowledge of its value is therefore
198 important for the computation of the electron diffusion and scattering performed in the
199 next section. For instance, Albert et al. (2020) found that the lifetimes for 1-2 MeV
200 electrons for $L=[1.5,2]$ was a factor of 4-5 times greater using a low-density model than
201 a high-density model. Because plasma density influences so greatly diffusion
202 coefficients, it is a source of a great amount of uncertainty in electron flux prediction
203 (Camporeale et al. 2016). The plasma density for our event period is derived by
204 procedure that combines Van Allen Probes data and models when data are lacking. The
205 density is first either derived directly from the upper hybrid resonance frequency
206 (Kurth et al., 2015) measured by EMFISIS, or when EMFISIS density is unavailable,

207 derived from spacecraft floating potential data calibrated against plasma densities
208 determined from the upper hybrid resonance frequency (Thaller et al., 2017). Spacecraft
209 floating potential is measured by the EFW instrument. Combining both techniques
210 allows to obtain the density the majority of the time (as shown and discussed below and
211 in Figure 3). Nevertheless, if the density from either technique is unavailable, the
212 procedure automatically replaces the unknown density by the statistical model of Albert
213 (1999) within the plasmasphere and the Sheeley et al. (2001) expression outside. In
214 these cases, the plasmopause location is needed to differentiate between the two
215 models. This is defined from the 100 #/cc level extracted from both EMFISIS and EFW
216 database or, if the 100 #/cc level (+/- 30%) is also undefined, we use the empirical
217 plasmopause model of Carpenter and Anderson (1992) with the knowledge of the K_p^*
218 index in order to separate the dense plasma from the low plasma density. When the
219 density is obtained from the measurements, as here in most cases, there is no need for
220 defining a plasmopause in the modeling.

221 Figure 3(top left) shows the plasma density from 1 to 10 of July 2014. We
222 accumulate all densities which fall into a given time bin i , t in $[t_i, t_i + \Delta t)$, and into a given
223 L bin j , L in $[L_j, L_j + \Delta L]$. This gives a 2-D matrix $[t, L]$, which has a set of values in each
224 cell (i, j) . For each cell, we then calculate the mean value of the density (and of all
225 quantity mentioned in the following). We choose a time scale of $\Delta t = 8$ h, as a
226 compromise between the time resolution (the lowest minimum time step between
227 perigee and apogee is $\Delta t = 4.5$ h.), a day integer fraction, and a not too prohibitive
228 computational time. This discretization gives 30 time samples for 10 days. We also
229 choose to treat 43 points in L shell, from $L = 1.3$ to $L = 5.5$ (by steps of $\Delta L = 0.1$), at which
230 values have been averaged over the available latitudes and MLT of the probes, resulting
231 in a fine grid of $43 \times 30 = 1290$ nodes, within which all models will be evaluated. This

232 method was first established in Ripoll et al., (2016a, 2017). Figure 3(left) shows that a
233 lack of density measurements occurs below $L=1.7$, where the density model of Albert et
234 al. (1999) replaces the missing observations, without any impact on this study. We will
235 also show below that the Sheeley et al. (2001) model is never used for this event as the
236 Van Allen Probes density is always defined below $L=5.5$.

237 The inner plasmasphere, defined here as a density larger than 100 #/cc, extends
238 up to $L\sim 5.5$ for the quietest times. Figure 3 (top right) shows the few cells below $L=5.5$
239 in which the density level goes below 100 #/cc. During the main substorm activity
240 associated with the AE peaks (Mauk and McIlwain 1974; Reeves et al., 1991; Sergeev et
241 al., 1998; Henderson, Reeves, et al., 2006; Henderson, Skoug, et al., 2006; Turner et al.,
242 2015) occurring during short durations (<8 hours) on July 3, 4, and 5, we observe short
243 local compression or erosion of the plasmasphere down to $L\sim 4.5$. The incoming HSSs on
244 July 10 is also visible. Comparing Figure 2 and 3 confirms the substorms on July 3 to 4, 7
245 and 9 affect the density. These perturbations of the plasmasphere by substorm
246 injections have direct consequences on the whistler-mode wave activity and will be
247 discussed further in the next section.

248 Figure 3 (bottom left) provides an alternative computation of the plasma density
249 based on observations of plasmaspheric hiss (Hartley et al., 2018). This new approach
250 has two direct interests. First, it provides a verification of the density level and a
251 replacement value when direct measurements are unavailable. Though this method
252 does contain some approximations, such as the assumption of parallel propagation, it
253 has been shown to provide results consistent with other methodologies (Hartley et al.,
254 2018). Second, it provides an indicator of the hiss activity; if the density can be inferred
255 from the hiss waves, it follows that hiss must be present at that time and location. We
256 can see that hiss waves were present below $L=5$ for the whole period, except during the

257 substorm activity on the July 3 and 4 and before the HSS on July 10. We will confirm
258 these interpretations in the next section from the wave observations. Limitation of the
259 computations to $L=5$ is not mandatory per se but guarantees greater accuracy of the
260 density values as the plasmasphere erosion and the absence of hiss occurs above $L=5$,
261 particularly as magnetospheric activity increases.

262 Figure 3(bottom right) shows the density is always obtained in our study from
263 Van Allen Probes measurements as the last L-shell of the known density largely exceed
264 $L=5.5$. One can define the plasmopause region as being somewhere between 100 #/cc
265 and 10#/cc. The region of 100 #/cc to 30#/cc highlighted in Figure (bottom right) could
266 be called the denser part of the plasmopause region. This region is often located above
267 $L\sim 4.7$ for this event, and above $L=5$ outside of the substorm injection, and is widely
268 spread over L-shell, except at the time of substorm injections. We will show below that
269 this region contains whistler-mode waves, likely whistler-mode hiss waves due to their
270 low mean frequency and to the high density shown in Figure 3(bottom left) (though
271 checking the microscopic structure is beyond the scope of this study), which will
272 contribute to electron scattering in the outer belt.

273 Malaspina et al. (2018) also found a correlation between whistler-mode hiss
274 wave power and the plasma density (for $L>2$), independent of geomagnetic activity; hiss
275 power increases with density. For instance, in Ripoll et al., (2019b) this correlation was
276 illustrated for various AE index, i.e. various substorm conditions indicative of the
277 magnetic activity (see also Malaspina et al., 2016). Density and hiss power are thus
278 coupled, with good knowledge of their values at all locations and all times being critical
279 to obtaining the best accuracy.

280

281 2.3 Wave properties

282 We use wave measurements from the EMFISIS instrument, restricting the
283 measurements to right-hand polarized waves with ellipticity (Santolik et al, 2002) above
284 0.2, and to a frequency range typical for plasmaspheric hiss from 50 Hz to 2 kHz
285 (Santolik et al., 2001; Hartley et al., 2018b). These criteria are still not sufficient to select
286 whistler-mode hiss waves only and can lead to the selection of whistler-mode chorus
287 waves at high L-shell during disturbed time. The knowledge of the density and the
288 plasmopause location can, in turn, help discriminate whether the whistler-mode waves
289 are indeed hiss or chorus. But this task still remains complex when the plasmasphere
290 density is at intermediate levels in the plasmopause region, between ~ 100 #/cc and
291 ~ 10 #/cc. We overcome that complexity by 1) identifying as best as possible the
292 plasmasphere and, therefore, the hiss location, 2) perform our computation of whistler
293 effects without trying to distinguish whistler-mode hiss waves from whistler-mode
294 chorus waves. The latter task is uncommon and made possible in this work because the
295 knowledge of all wave and plasma properties is locally available such that no statistical
296 model is involved for either statistical hiss or chorus wave properties. It should be
297 noticed that high frequency whistler mode waves occurring in low-density regions
298 (below 30 /cc) are assimilated to chorus waves in this study, although the microscopic
299 structure of these waves has not been checked. The main limitation of our method
300 comes from the upper frequency we impose on the whistler-mode waves (2 kHz), which
301 results in the exclusion of higher frequency waves (e.g. upper band chorus waves) from
302 this analysis. Missing the upper band of the chorus frequency spectrum leads to an
303 underestimation of pitch angle diffusion at low energy (<100 keV) for $L > 4.5$. This is not
304 a concern for this study since we focus on >100 keV electrons.

305 Figure 4 shows the whistler-mode wave properties for the period of interest, and
306 that enter in the computation of hiss pitch angle diffusion effects (cf. Ripoll et al., 2017

307 for their definition). Figure 4 (left) shows the mean value of the whistler-mode wave
308 frequency for each node. Figure 4(right) shows mean values of the wave power spectra,
309 accounting for Magnetic Local Time (MLT) dependence of the wave amplitude using the
310 Spasojevic et al. (2015) model. The mean wave vector angle, θ_m , calculated from data
311 obtained by the Singular Value Decomposition method of Santolik et al. (2003), and the
312 mean wave vector width $\Delta\theta_m$ are also plotted in Figure 4. A filamentary temporal
313 structure of both frequency and amplitude hiss wave data is very apparent. The mean
314 frequency shows three populations, two for hiss and one for chorus. The first is between
315 200–400 Hz and the second is at higher frequencies between 600–800 Hz. Both
316 correspond to whistler-mode hiss waves that occupy most of the domain of the study.
317 Some rare incursions of chorus waves above $L=5.2$ are visible, with a mean frequency
318 that exceeds ~ 1000 Hz. These chorus incursions are synchronized with the lowest
319 densities observed in Figure 3. Structures change in time and space in a dynamic and
320 complex way as the satellite orbits around the Earth. Wave amplitudes vary by orders of
321 magnitude. The stronger hiss waves are located in the plasmasphere interior, between L
322 $= 2$ and $L = 4$. The mean wave normal angle and mean wave normal width are rather
323 homogeneous, with a moderate global mean value of the wave normal angle close to 40° .
324 In the rare case of large wave normal angles, above $\sim 60^\circ$, pitch angle diffusion
325 drastically reduces and electron lifetime increases (Ripoll, Albert, and Cunningham,
326 2014; Albert, 2017). We find some similarities with the wave observations made in
327 Ripoll et al. (2017) for a quiet event in March 2013.

328

329 **3. Computation of diffusion coefficients**

330 **3.1 Validity of the approximations used in the model**

331 In this study, bounce averaged diffusion coefficients $D_{\alpha_0\alpha_0}(L, E, \alpha_0, t)$ are
332 computed following the equations of Lyons et al. (1972), which uses both the low
333 frequency ($\omega_m/\omega_{ce0} < 1$) and the dense plasma ($\omega_m\omega_{ce0}/\omega_{pe}^2 \ll 1$) approximations. To
334 demonstrate the validity of these assumptions, these quantities are plotted in Figure 5
335 (center) and (right). Both of these approximations have been shown to be reliable in the
336 plasmasphere (Albert, 1999; Glauert and Horne, 2005) due to the dense plasma, large
337 magnetic field, and the dominance of low-frequency whistler-mode waves. Furthermore,
338 they have been shown to be more generally applicable to the plasmasphere during quiet
339 times, when the plasmasphere expands out to $L \sim 5.5$ (Ripoll et al., 2017, 2019a). Figure 5
340 demonstrates that these approximations still hold during the moderate perturbations
341 brought by substorm activity. Only on July 3rd (date of the largest substorm) and on July
342 10th (date of the HSS) for $L > 5.2$ (4 cells), are these approximations close to being
343 violated, with $\omega_m\omega_{ce0}/\omega_{pe}^2 > 0.01$. We note that this may introduce some inaccuracy of
344 our results at these dates and locations. This approximation is applicable primarily due
345 to the low frequency of the whistler-mode waves, which compensate for the low density
346 associated to the erosion of the plasmasphere during the substorm activity. During the
347 various substorms on July 3, 4, and 7, as well as during the HSS on July 10, we note that
348 ω_{pe}/ω_{ce0} (Figure 5, left) drops by a factor ~ 4 , from 20-25 down to ~ 6 , a clear indicator
349 of the plasma density decrease.

350

351 3.2 Diffusion coefficients

352 The computation of the bounce- and drift- averaged equatorial pitch-angle
353 diffusion coefficient is performed for each 8 h interval at each L-shell (0.1 L resolution)
354 based on the observed wave properties described in section 2. Mathematical
355 expressions of the diffusion coefficients can be found in (Lyons et al. 1972; Albert, 1999;

356 Albert, 2005; Glauert and Horne, 2005) and are not recalled here. Diffusion coefficients
357 are computed for 60 energies (E varying from 0.07 MeV to 6MeV) at every node (t, L),
358 i.e., 75 600 times ($43L \times 30t \times 60E$). A grid of 256 pitch angles in $[0, 90^\circ]$ and n cyclotron
359 harmonics is used, with the harmonic number determined by an estimate (Mourenas
360 and Ripoll, 2012). A massively parallel supercomputer is required to generate this
361 database of 19.3M diffusion coefficients, with a total cost of computation of ~ 12
362 hours/processor for ~ 1300 processors, i.e. ~ 15600 hours for our ~ 10 -day event.

363 The result is a data-derived, time-varying diffusion coefficient, $D_{\alpha_0\alpha_0}(t, L, E, \alpha_0) =$
364 $D_{\alpha_0\alpha_0}(f_m(t, L), \Delta f(t, L), \theta_m(t, L), \Delta\theta(t, L), n_e(t, L), E, \alpha_0)$, which depends on (t, L)
365 through the mean wave frequency, f_m , the wave frequency width, Δf , the mean wave
366 normal angle, θ_m , the wave normal angle width, $\Delta\theta$, and the plasma density, n_e .
367 Dependence on energy, E , and equatorial pitch-angle, α_0 , is inherited from the resonance
368 and dispersion relations used for deriving $D_{\alpha_0\alpha_0}$. Time-varying diffusion coefficients are
369 plotted in Figure 6 at $L=3.5$ and $L=4.5$, with each panel showing the first 8h for each day
370 of the event (307 200 values, 1.6% of the database). It is evident that the diffusion
371 coefficients are highly variable from one day to the next. This is due to the variability of
372 the wave properties and the plasma density. Typically, the wave normal angle influences
373 the diffusion profile; a low wave-normal angle produces cyclotron diffusion which
374 increases with pitch angle, whereas an intermediate wave-normal angle produces
375 cyclotron diffusion that is approximately constant with respect to pitch angle. We
376 observe higher diffusion coefficients, for instance on the 07/01 and on 07/05, which
377 coincides with non-perturbed times. It is important to note that wave properties are
378 correlated together as well as correlated with the plasma density as previously
379 discussed (and in Malaspina et al. 2016, 2018; Ripoll et al., 2016a, 2017, 2019a, 2019b).
380 Computing time-varying diffusion coefficients, as done here, allows us to keep all these

381 correlations. The alternative method (not chosen here) of averaging each wave property
 382 and the plasma density separately before plugging them into a single diffusion
 383 coefficient, i.e. $D_{\alpha_0\alpha_0}(\widehat{f_m(L)}, \widehat{\Delta f(L)}, \widehat{\theta_m(L)}, \widehat{\Delta\theta(L)}, \widehat{n_e(L)}, E, \alpha_0)$ or
 384 $D_{\alpha_0\alpha_0}(\widehat{f_m}, \widehat{\Delta f}, \widehat{\theta_m}, \widehat{\Delta\theta}, \widehat{n_e}, E, \alpha_0)$ (e.g. Zhu et al., 2019) in which $(\widehat{\cdot})$ denotes a temporal or
 385 both a temporal and a spatial averaging, cannot conserve the various correlations
 386 between the various properties and introducing *de facto* an error. Solving for the
 387 diffusion coefficients at small time and spatial scales allows us to avoid any artificial
 388 numerical smoothing that inevitably occurs if one uses averaged wave and plasma
 389 properties.

390 Figure 7 shows the averaged diffusion coefficients used for the simulation, at 4
 391 selected L-shells. This diffusion coefficient is computed from the temporal average of the
 392 30 time-varying diffusion coefficients at each (L, E, α_0) :

$$393 \quad \widehat{D_{\alpha_0\alpha_0}}(L, E, \alpha_0) = (D_{\alpha_0\alpha_0}(f_m(t, L), \widehat{\Delta f(t, L)}, \theta_m(t, L), \Delta\theta(t, L), n_e(t, L), E, \alpha_0))$$

394 Figure 7 shows that pitch angle diffusion occurs at lower energy as L increases. At L=2.5,
 395 one can easily distinguish cyclotron diffusion (the upper left green region) from the
 396 Landau diffusion above $\sim 75^\circ$, both separated by a wide region of extremely weak
 397 (Landau) diffusion (in blue). This region of extremely weak diffusion shrinks with
 398 increasing L as cyclotron diffusion reaches both higher pitch angles and lower energies.

399

400 3.3 Lifetime

401 Electron lifetimes, i.e. the e-folding time scales, τ , in days, are computed from the
 402 averaged diffusion coefficients following the original method of Lyons et al. (1972). That
 403 method is discussed and explained in greater detail in Ripoll et al., (2016b) and shall not
 404 be recalled here. It has been proven extremely robust when used to generate lifetimes
 405 from several millions of diffusion coefficients in Ripoll et al. (2014).

406 The electron lifetime profile is particularly interesting and characteristic when
407 plotted daily in the (L, E) plane (Meredith et al., 2006b; Ripoll et al., 2014a, 2016b;
408 2017). There are two comments of importance that are evident from these lifetimes
409 during our period of interest shown in Figure 7. First, electron lifetimes are similar in
410 both shape and amplitude to those obtained during the quiet period of March 2013. The
411 shape follows a complex and dynamic filamentary structure, directly inherited from the
412 wave properties. Average electron lifetimes are of the order of 1–10 days when waves
413 are active and at the energies where the resonance causes maximal diffusion. The
414 absence of pitch angle diffusion from whistler-mode waves for inner belt electrons
415 below ~ 800 keV (Fennell et al. 2015) causes lifetimes in excess 100 days (see
416 Claudepierre et al. 2020 for recent apparent lifetimes extracted from Van Allen Probes
417 data). Theoretically, lifetimes can be much larger and the time to reach equilibrium, so
418 that decay is steady enough to be described by lifetimes, can itself be quite large, in
419 particular in the inner belt (Ripoll et al. 2016b). Large lifetimes explain why inner belt
420 electrons below 1 MeV are so stable and can remain trapped for many months. It is
421 worth noting that despite lightning-generated whistlers being commonly observed in
422 the inner belt, with their amplitude recently reported from the Van Allen Probes
423 measurements in (Ripoll et al. 2020b), they are disregarded in this study. This is due to
424 the fact that their amplitudes are typically too weak to contribute significantly to fast
425 losses occurring within 10 days (Meredith et al., 2007, 2009; Ripoll et al., 2019d). For
426 quiet times with a greatly extended plasmasphere, effects on low-energy electrons
427 (< 300 keV) extend to the outer belt, to $L = 5.5$. Such a plasmasphere configuration is
428 essential to understanding the decay of outer belt electrons from whistler-mode waves.
429 Whistler-mode waves predominantly act along a main diagonal line in the (L-shell,
430 Energy) plane, which decreases with increasing L-shell (Lyons and Thorne, 1973).

431 Electron lifetimes along this diagonal are close to 1 day attesting to strong pitch angle
432 scattering, predominantly due to whistler-mode hiss waves. Electron lifetimes remain
433 low as energy increases from 200 keV up to 2 MeV; at 1 MeV the lifetime is 3.5 days at
434 $L=3.0$, 9 days at $L=4.0$, 7 days at $L=5.0$, and 21 days at $L=5.5$.

435 The second comment of importance concerns the two zones that are observable
436 in the lifetime profile, one below $L\sim 4.7$ and the other above, with low lifetimes
437 seemingly shifted up in energy. In actuality, this is not a shift in energy since the lifetime
438 decreases homogeneously in energy; lifetimes are simply lower. This effect is the net
439 result of various effects acting oppositely. This reduction in electron lifetimes could be
440 directly associated with a decrease in the plasma density. From Figure 3 (top), it is
441 apparent that the lowest density does indeed occur above $L\sim 4.7$ (cf. the black region).
442 This density decrease is attributed to the increase in the AE index and to the substorm
443 activity, as explained in section 2. Therefore, we may postulate that the moderate
444 substorm activity leads to a lower plasma density in the outer belt, above $L\sim 4.7$, that in
445 turn lowers the electron lifetime. But evaluating individual diffusion coefficients for L-
446 shell at $L=4.8, 4.9, 5., 5.1$, by step of 8 hour (Figures not shown), we do not observe a
447 noticeable increase in the diffusion coefficients associated with the substorm injection
448 and attributed to the lowering of the density, though theoretically speaking lowering the
449 density does lower the electron lifetimes (all other parameters unchanged). This
450 scenario is possible, and likely happening to some extent, and could occur for other
451 events. However, we find that pitch angle diffusion is actually lower (higher lifetimes)
452 during the substorm injections, despite the lower plasma density. This is due to the
453 whistler-mode wave amplitude decreases that occur during July 3, 4, 7 and 10, each
454 associated with substorm injections (cf. Figure 2-3). These reductions in wave amplitude
455 contribute to lower pitch angle diffusion, which directly increases electron lifetimes. The

456 decay of the whistler-mode wave amplitude becomes more important on average than
457 the decay of the density. That is, the mean lifetime increases during substorm activity.
458 The decrease in the mean electron lifetime above $L \sim 4.7$ can be explained by the
459 enhancement of whistler-mode waves during the reasonably quiet times that occur
460 between the substorm injections, such as on July 5 in Figure 6. The substorm activity is
461 weak enough that the moderate compression (or moderate erosion) of the
462 plasmasphere does not cause the whistler-mode hiss waves to vanish with it. We can
463 conclude that pitch angle diffusion by whistler-mode waves has various characteristic
464 features of opposite effect; first, during the injection, there is a lowering of the whistler-
465 mode wave amplitude which increases lifetimes and also a decay of the density which
466 lowers lifetimes, and, second, in between the substorm perturbations, there is a
467 strengthening of the whistler-mode waves which lowers the mean lifetime. When
468 combined, all three effects lead to a mean enhancement of loss above $L \sim 4.7$ in our event.
469 Finally, the density drop associated with the substorm injections is also likely to cause
470 changes in the wave properties such as the mean frequency, at least when the chorus
471 incursion occurs leading to a higher mean frequency. Would these features still be
472 apparent if we had used statistical diffusion coefficients (or lifetimes) that cannot keep
473 all plasma and wave properties correlated?

474

475 **4. Observations and Fokker-Planck simulations**

476 3.1 Van Allen Probes flux observations

477 Figure 8 shows 27 electron flux snapshots observed by the Van Allen Probes in
478 the (L, E) plane, taken each outbound pass (every ~ 9 h) where data are available from 30
479 June 2013 to 9 July 2013. These snapshots are constructed from MagEIS observations
480 (Blake et al., 2013) with the Level 2 spin-averaged flux interpolated onto a regular fixed

481 grid in L. Spin-averaged fluxes have been shown to accurately represent the
482 omnidirectional flux that can be generated using Level 3 MagEIS measurements (Ripoll
483 et al., 2019a). Note that the background correction algorithm of Claudepierre et al.
484 (2015) has been applied to the MagEIS electron flux measurements shown here.

485 The snapshots of Figure 8 are similar to the original format presented in Reeves
486 et al. (2016), and also those used in Ripoll et al. (2016a, 2016b, 2017, 2019a, 2019b).
487 The main substorm injection of electrons is apparent on July 3, with higher flux in the
488 outer belt observed below 200 keV (e.g. Turner et al., 2015). The substorm of July 4 is
489 too weak to be visible; the flux of new incoming electrons at $L \sim 5$ is likely balanced by
490 the strong loss of the older outer belt electrons below 200 keV. The substorm on July 7
491 leads to a slight increase of the flux at the lowest energies. The high-speed stream
492 injection at the end of the event, on July 10, is also visible. There is a good concordance
493 between the observed flux decay and the low electron lifetimes in the (L, E) plane. The
494 slot region progressively enlarges, and the outer belt flux drastically decays during this
495 10-day period as substorm injections modify only the low energy structure. Since the
496 beginning of the event, there is a characteristic quiet time S-shape to the inner boundary
497 of the outer belt when drawn in the (L, E) plane reported by Reeves et al. (2016) and
498 computed in Ripoll et al. (2016a, 2016b, 2017, 2019a, 2019b). When most of the high
499 energy part of the outer belt has decayed after 10 days, with little flux left (omitting low
500 energy injections below 200 keV), there exists a remnant pocket of trapped electrons,
501 for L in [4.7, 5.2] and E in [1, 2] MeV, that constitutes the remains of the upper loop of
502 the 'S', first discussed in Ripoll et al. (2019a).

503

504 3.2 Simulations

505 The temporal evolution of the gyro, bounce, and drift phase-averaged phase
 506 space density, $f(t, L, E, \alpha_0)$, in the presence of pitch-angle diffusion can be described by
 507 (*Schulz and Lanzerotti, 1974; Shprits et al., 2008*):

$$508 \quad \frac{\partial f}{\partial t} = \frac{1}{G} \frac{\partial}{\partial \alpha_0} \Big|_{L,E} \left(G \widehat{D_{\alpha_0 \alpha_0}} \frac{\partial f}{\partial \alpha_0} \Big|_{L,E} \right) \quad (1)$$

509 with $\widehat{D_{\alpha_0 \alpha_0}}$ computed in section 3 (cf. Figure 7) and $G = T(\alpha_0) \sin(2\alpha_0)$. $T(\alpha_0)$ is
 510 proportional to the bounce period evaluated at the equatorial pitch-angle, α_0 . We use
 511 $f(\alpha_{0,lc}) = 0$ at the loss cone, which itself is computed from a dipolar magnetic field. A
 512 Newman boundary condition is used at 90° , $\frac{\partial f(t, \alpha_0)}{\partial \alpha_0} = 0$. Equation (1) neglects radial
 513 diffusion and off-diagonal terms in the diffusion tensor. The numerical method and code
 514 are described in Réveillé et al. (2001). The absence of radial diffusion makes it
 515 impossible to solve for any injections associated with the substorm activity. In addition,
 516 energy diffusion is neglected in this study since energy diffusion coefficients are
 517 negligible for whistler mode hiss waves (e.g. Albert, 2008) on which that study focuses.
 518 Only scattering from pitch angle diffusion, and how the effects of whistler-mode waves
 519 are affected by the substorm activity, are investigated in this section.

520 Figure 9 shows the omnidirectional flux, i.e. the phase space density integrated
 521 with respect of pitch angle, solution of Equation 1 at each L-shell and energy. In this first
 522 numerical experiment, we choose the initial condition as $f(t = 0, L, E) = \cos^2(\alpha_{0,lc}) -$
 523 $\cos^2(\alpha_0)$. This function guarantees a smooth transition at the loss cone where $f=0$ and is
 524 homogeneous with respect to energy. This allows all particles to decay from their initial
 525 state and for us to better understand and quantify their loss. Results immediately show
 526 the two distinct regions, below and above $L \sim 4.7$, with the region above $L \sim 4.7$ showing
 527 more important scattering, as discussed in section 3.3. Interactions with whistler-mode
 528 waves are particularly strong below 150 keV for $L > 3.5$, with the omnidirectional flux

529 decaying by more than 5 orders of magnitude in 10 days (Figure 9 is saturated at level -5
530 in order to see details at higher energies). This low energy region (<150 keV) is highly
531 dynamic; with injections required to be both numerous and fast in order to bring new
532 electrons to lower L-shells and overcome the losses due to whistler-mode waves, as
533 seen in the observations in Figure 8. More generally, Figure 9 describes the decay
534 associated with the formation of a wide slot region. Above $L \sim 4.7$, we see a significant
535 decay of the omnidirectional flux in the outer belt up to ~ 1 MeV, similar to observations.
536 Whistler-mode waves have little effect on the remnant pocket of electrons observed in
537 Figure 8 at L in [4.7, 5.2] for E in [1, 2] MeV, with the omnidirectional flux decaying by
538 barely half an order of magnitude in the simulations.

539 The second numerical experiment uses the same pitch angle profile, this time
540 combined with the energy spectrum from the MagEIS spin-averaged L2 flux on the
541 06/30/2014 (6.54am-11.31am) (cf. first panel of Figure 8). The results of this
542 simulation are plotted in Figure 10, and are the best representation of the losses that we
543 believe are occurring in the slot region and in the outer belt during this event. Various
544 important features are apparent: i) the inner belt, defined as ~ 1 MeV electrons below
545 $L=2$ (at the edge of the simulation domain) or ~ 100 keV electrons below $L=3.5$, is
546 unaffected by whistler-mode waves; ii) the slot region is formed in ~ 10 days along the
547 diagonal and is primarily driven by pitch angle diffusion caused by whistler-mode waves
548 (cf. early observations of 35-560 keV electrons from Lyons and Williams (1975)); iii) the
549 outer belt flux decays strongly below ~ 1 MeV; iv) three complex substorm conditions
550 (cf. section 3) explain why the significant loss reaches up to 1 MeV electrons in the outer
551 belt; v) the remnant pocket of trapped electrons (L in [4.7, 5.2] for E in [1, 2] MeV)
552 decays very slowly, extending to $L=5.5$ in the simulation due to lack of outward radial
553 diffusion, and becomes increasingly apparent as the outer belt decays; and vi) the

554 injections of low energy electrons (below ~ 150 keV and absent of the simulations)
555 associated with substorm activity (up to 300 keV for the strongest substorm) are
556 required to be numerous and fast (e.g. Friedel et al., 1996; Turner et al., 2015) to
557 compensate the intense loss. Finally, comparing the results of Figure 10 with the
558 observations of Figure 8, we see qualitative agreement for both the daily enlargement of
559 the slot and for the significant reduction of the outer belt. Reproduction of these key
560 features is highly encouraging, and demonstrates that this method has the ability to
561 model reasonably electron scattering during quiet time dynamics, perturbed (or not) by
562 moderate substorm activity.

563 The main limitations of this study relate to; i) the lack of inward transport
564 (usually modeled by radial diffusion) that does not allow reproduction of the substorm
565 injections, ii) the approximations used in the diffusion coefficients (cf. section 3.1), and
566 iii) the magnetic local time (MLT) description that is subsequently discussed. The
567 measurements of frequencies and wave normal angles used here are made locally in
568 MLT, though they are applied to all MLTs. Only the wave amplitude is rescaled by the
569 MLT dependence given by Spasojevic et al. (2015). We believe variation of the wave
570 properties (frequency and mean wave normal angle) to have only minor effects (unless
571 changes are drastic, which is possible [Hartley et al., 2018b]). However, variations in the
572 plasma density with MLT, and the possible development of higher frequency whistler-
573 mode waves, i.e. chorus, in regions of lower density (cf. Figure 3), could affect the
574 accuracy of these simulations since decaying plasma density, caused by substorm
575 activity, is found to have important repercussions. Another caveat of the method is that
576 if the inward motion of the plasmapause is localized where we observe it (or if it is only
577 an apparent motion because of field line stretching) then most of the electron drift orbit
578 is still in the plasmasphere and experiences whistler-mode hiss in a way it may not have

579 a significant effect on the drift-averaged pitch angle diffusion. Both of these problems
580 have no current solution since they are related to the uniqueness of the observation at a
581 given MLT and the absence of availability of any other, leading to speculations about
582 possible situation scenarios along the drift. Finally, there could be acceleration occurring
583 in the rare regions of wave intensification identified in Figure 4 and in the low-density
584 regions highlighted in Figure 3, but the phenomena are too limited in space or/and in
585 time to believe they would significantly matter for this event.

586 The alternative of using statistical models sorted in MLT has little chance of
587 increasing accuracy. Validation would also be an issue as the observed fluxes would be
588 measured at the same MLT. What is encouraging is the synchronization of global indices
589 (like AE here) with local observations, which goes in favor of the generalization of the
590 observations. On the other hand, the location of the whistler-mode waves, which are not
591 uniformly distributed over MLT, is an issue that unavoidably requires the introduction
592 of an MLT-dependence. The only viable alternative, which does not yet exist, is multiple
593 synchronized measurements at various MLT and at fixed L-shell. It is hoped that new
594 radiation belt missions could aim to resolve this issue (e.g. Millan et al., 2019; Ripoll et
595 al., 2020). For now, the only viable approach is to include these necessary
596 approximations in our models and to quantify the accuracy of the results against
597 observations of the decaying radiation belt flux, as it has been done in this study.

598

599 **5. Conclusions**

600 In this work we study the dynamics of radiation belt electrons during a
601 geomagnetically reasonably quiet period perturbed by moderate substorm activity and
602 preceding a high-speed stream (HSS), with the aim of obtaining a global description of
603 the pitch angle scattering occurring in the radiation belts in L-shell [2, 6], and energy

604 [0.1, 10] MeV. The goal is to assess whether the event-driven methodology, which has
605 been successfully applied for quiet conditions (Ripoll et al., 2016a, 2017, 2019a, 2019b),
606 can also obtain a high degree of accuracy when the radiation belts are perturbed by
607 moderate substorm activity.

608 For the event studied we show that the plasmasphere extends up to and beyond L
609 = 5, which provides favorable conditions for whistler-mode waves reaching out, and
610 scattering, outer belt electrons. Substorm injections result in low density plasma
611 extending down to $L \sim 4.5$, although these periods last less than 8h. Whistler-mode
612 waves, mostly plasmaspheric hiss, predominantly act along a main diagonal line in the
613 (L, E) plane, decreasing in energy with increasing L -shell. This diagonal is well marked
614 for quiet events, but shifts up in energy at $L \sim 4.7$ in this case due to the substorm
615 activity, thus allowing the scattering of up to 1 MeV electrons in the outer belt. Whistler-
616 mode waves drive major loss phenomena which contributes to both the creation of a
617 wide slot region and significant decay of the outer radiation belts below 1 MeV. A good
618 qualitative agreement is found between the observed daily flux from the Van Allen
619 Probes and the computed flux from quasi-linear resonant interactions between
620 electrons and whistler-mode waves.

621 A main result of this study, brought thanks to the high temporal and spatial
622 resolution of the event-specific pitch angle scattering model in use, is the mean
623 enhancement of the electron pitch angle scattering above $L \sim 4.7$, which we attribute to
624 substorm activity. We have demonstrated that the observed substorm activity coincides
625 with a short diminution of the plasmaspheric density, in a way that is moderate enough
626 to conserve a plasmaspheric density of ~ 100 #/cc, or higher, at $L=5.5$ at times different
627 than the injection time (± 4 h). This has two direct consequences. First, the
628 conservation of the plasmasphere at high L -shell (above 5) allows whistler-mode hiss

629 waves to remain, exist, and continue contributing to the lowering of the flux level in the
630 outer belt. Second, while the lowering of the density associated with the substorm could
631 increase pitch angle diffusion via wave-particle interactions, we find that this effect does
632 not compensate the whistler-mode wave amplitude decay, which occurs simultaneously
633 during the substorm injections. That is, pitch angle diffusion actually becomes weaker
634 during the substorm injections (+/-4h). However, whistler-mode waves are enhanced in
635 the periods between the substorm injections, due to the widely extended plasmasphere
636 out to, and above, $L=5.5$. The combination of these opposing effects leads to pitch angle
637 scattering by whistler-mode waves that is, on average over the 10-day period, enhanced
638 above $L \sim 4.7$. This allows the scattering of up to 1 MeV electrons in the outer belt but is
639 not sufficient to significantly decay the remnant pocket of relativistic electrons between
640 1 and 2 MeV located at L in [4.7, 5.2], for which both observations and simulations show
641 an omnidirectional flux that decays only slightly in 10 days.

642

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657

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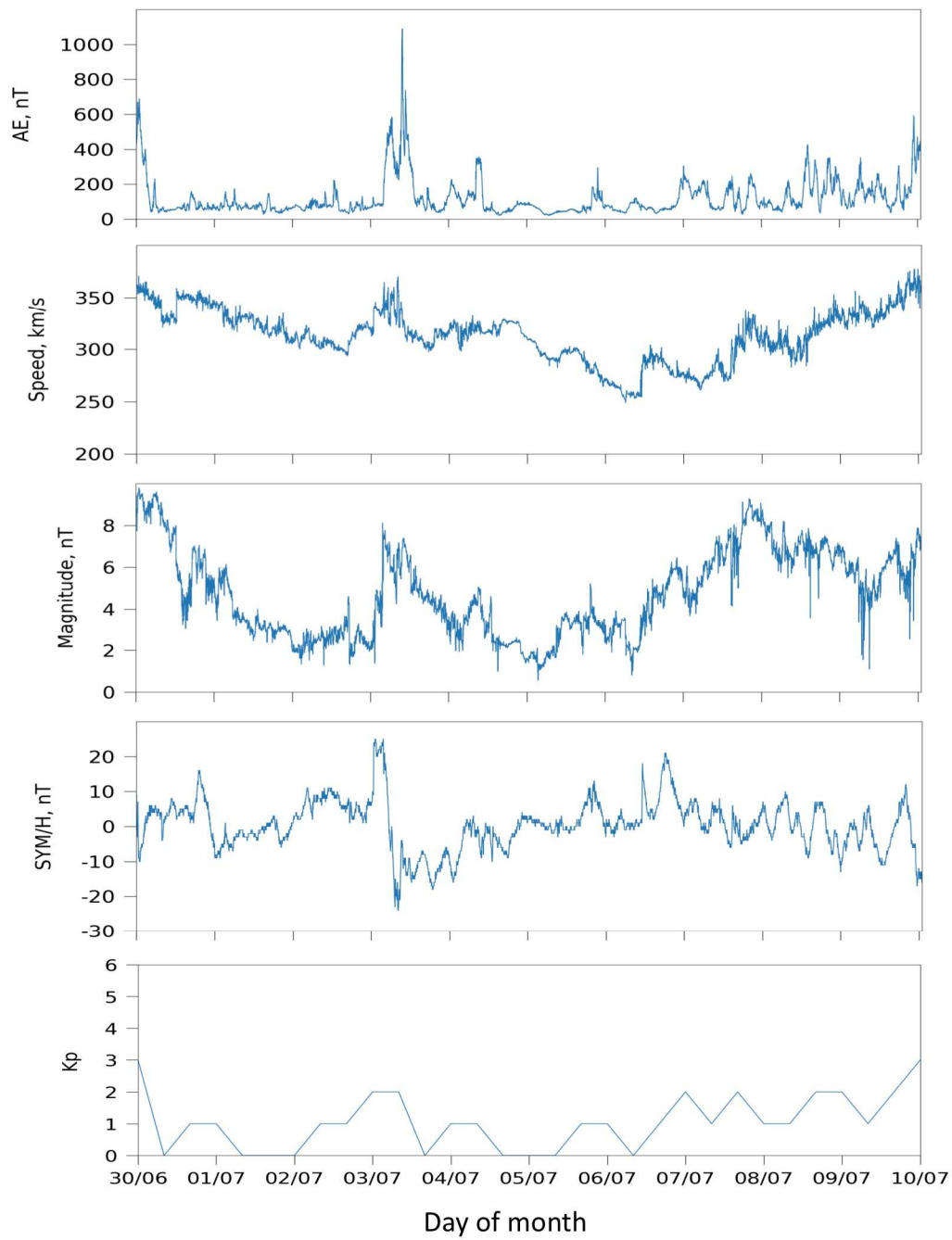
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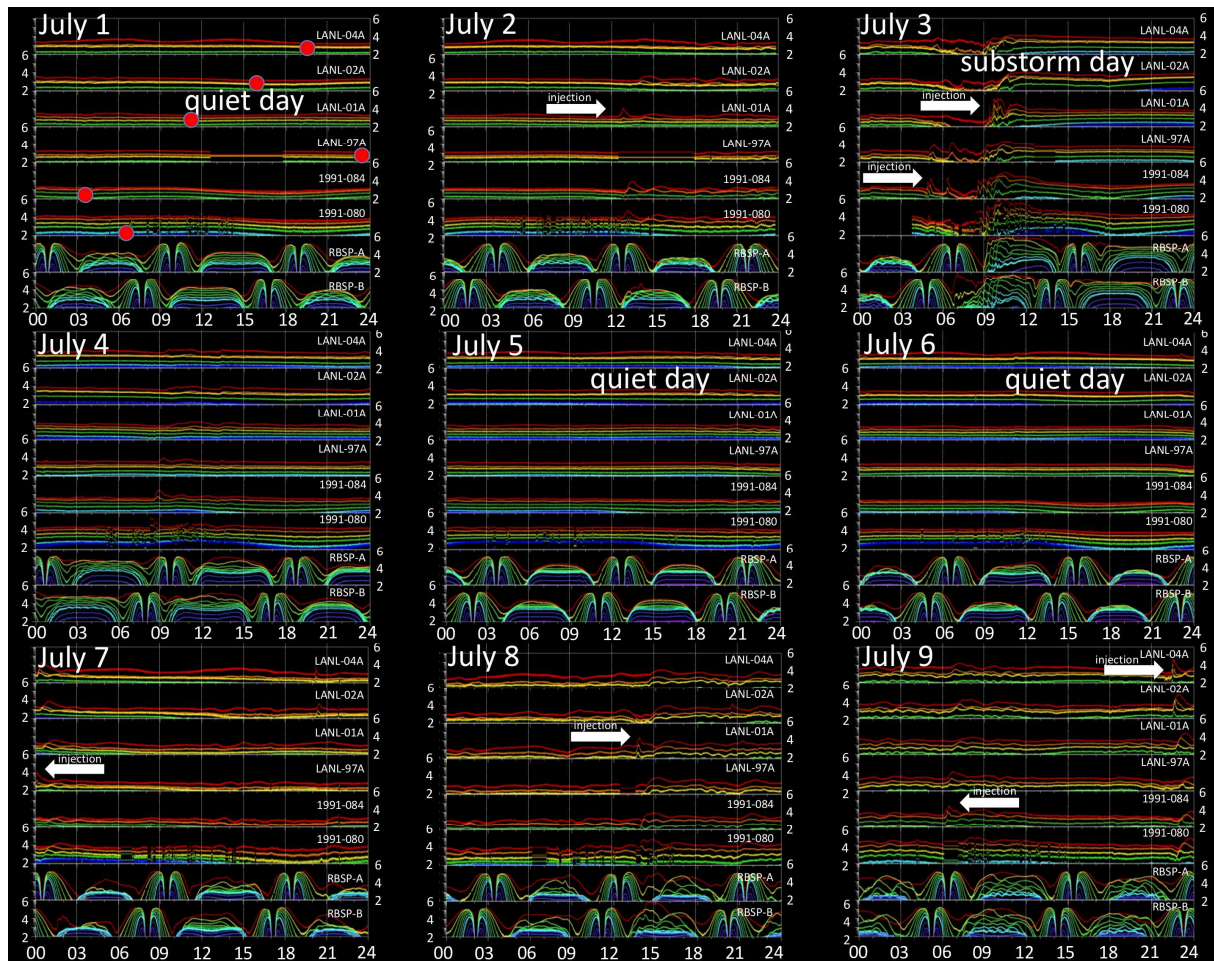


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876 Figure 1: From top to bottom: AE index, solar wind flow speed, interplanetary magnetic
877 field magnitude average, SYM/H index (source <https://omniweb.gsfc.nasa.gov/>).

878 Averaged Kp index taken per period of 8 hours between June 30 and July 10 2014.

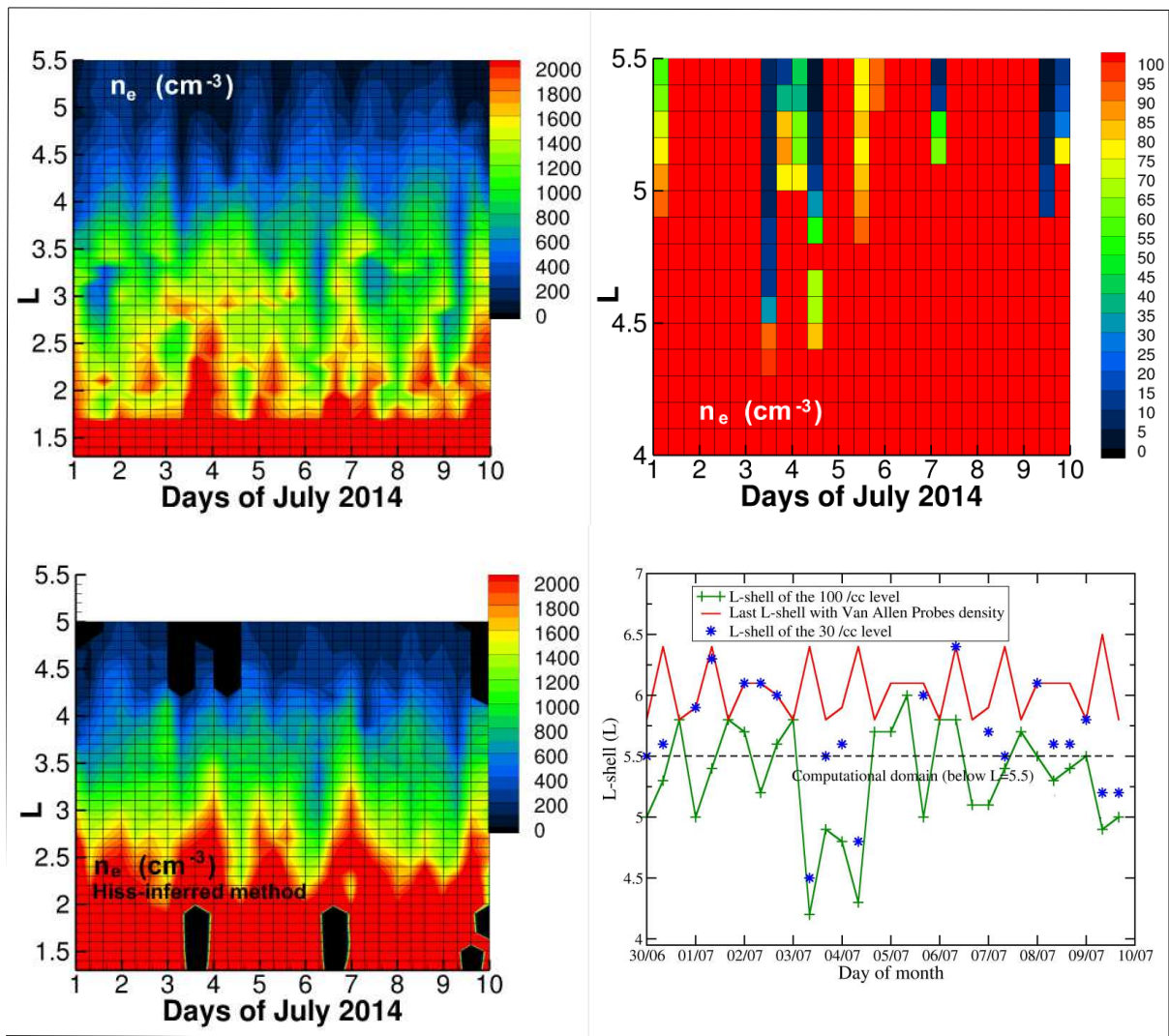
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882 Figure 2: LANL-GEO (from top to bottom: LANL-04A, LANL-02A, LANL-01A, LANL-97A,
 883 1994-084, 1991-080) and Van Allen Probes (RBSP B and RBSP A) survey electron flux
 884 from 1 to 10 July 2014 with one panel per day. This figure shows rather quiet days (on
 885 July 1, 5, 6) and mild (on July 2, 4, 7) to moderate (on July 3, 8, 9) perturbations from
 886 substorm activity. White arrows point to some of the main injections. (red circle) Local
 887 MLT midnight for each LANL-GEO satellite changes by less than five minutes during the
 888 10-day period (1991-080: 6.33, 1991-084: 3.33, LANL-97A: 23.38, LANL-01A: 11.29,
 889 LANL-02A: 15.43, LANL-04A: 19.53).

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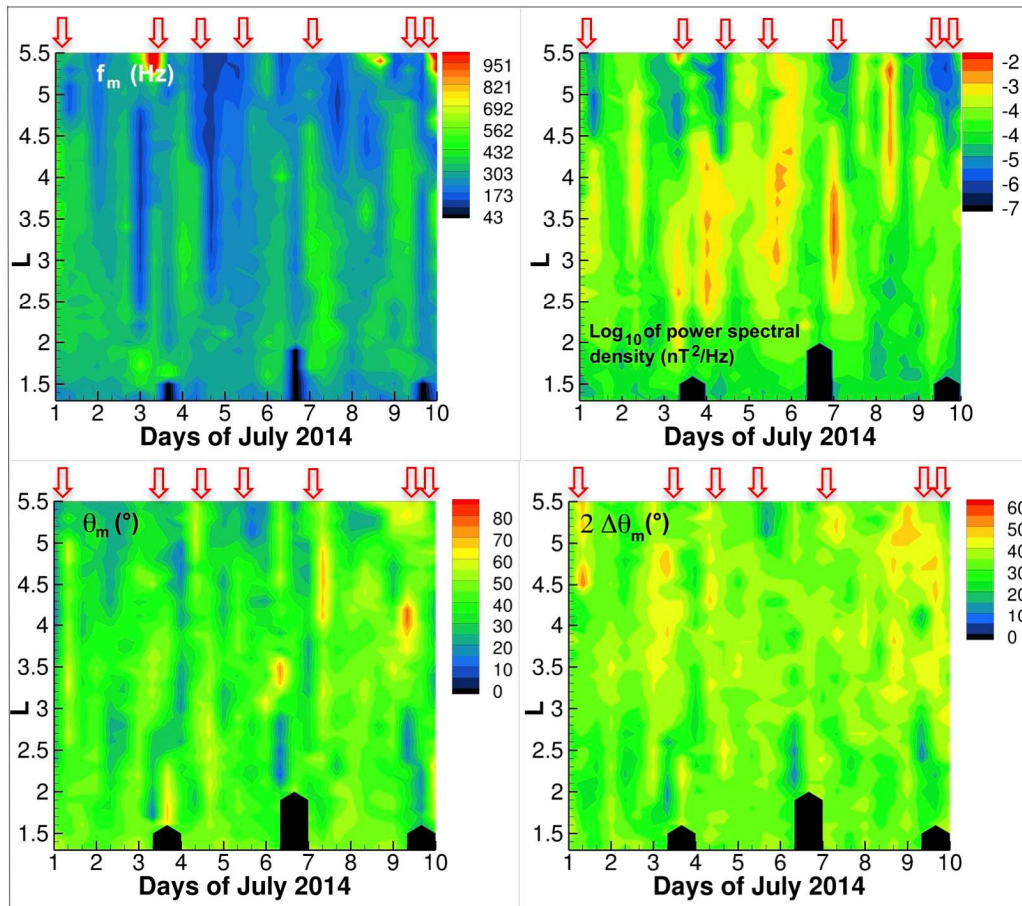
893 Figure 3: Evolution of the plasma density during the first 10 days of July 2014. (top left)
 894 plasma density from EMFISIS. (top right) Zoom above $L=4$ for density below 100 #/cc in
 895 order to define the plasmopause region. (bottom left) Estimation of the plasma density
 896 up to $L=5$ from the whistler-mode hiss waves used as a verification of the density and
 897 the hiss presence. (bottom right) L -shell of the last Van Allen Probes known density, 100
 898 /cc density level, and 30/cc density level showing all plasmas densities used in the
 899 domain of this study come from Van Allen Probes measurement. The region of density
 900 between 30/cc and 100 /cc, defined here as the *dense* plasmopause region, is a widely

901 spread region over L-shell, except during short times of injections and compressed
902 plasmasphere.

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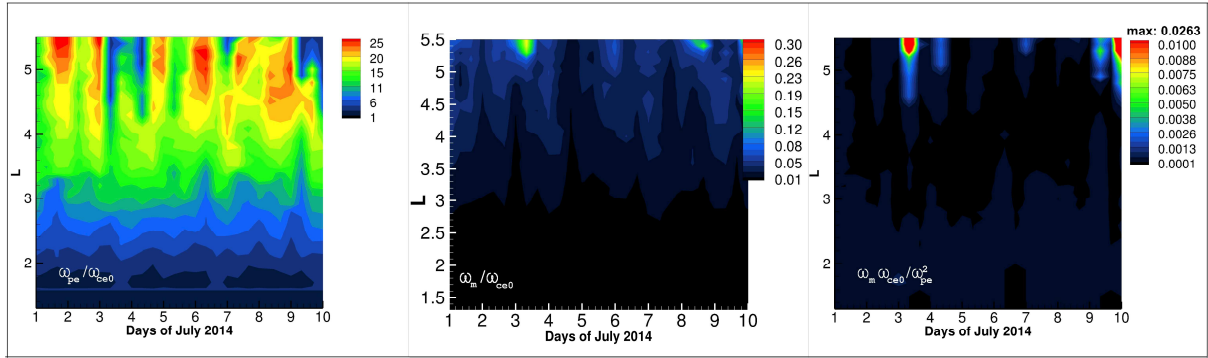
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907 Figure 4: Evolution of the whistler-mode wave properties during the first 10 days of July
908 2014; (top left) mean frequency, (top right) wave power spectral density, (bottom left)
909 mean wave normal angle and (bottom right) wave normal angle width. Most of the
910 whistler-mode waves here are plasmaspheric hiss. Exceptions occur, for instance, on
911 July 3 and 10. The times at which the plasma density (cf. Figure 3) is perturbed by
912 substorm injections (cf. Figure 2) are identified by red arrows.

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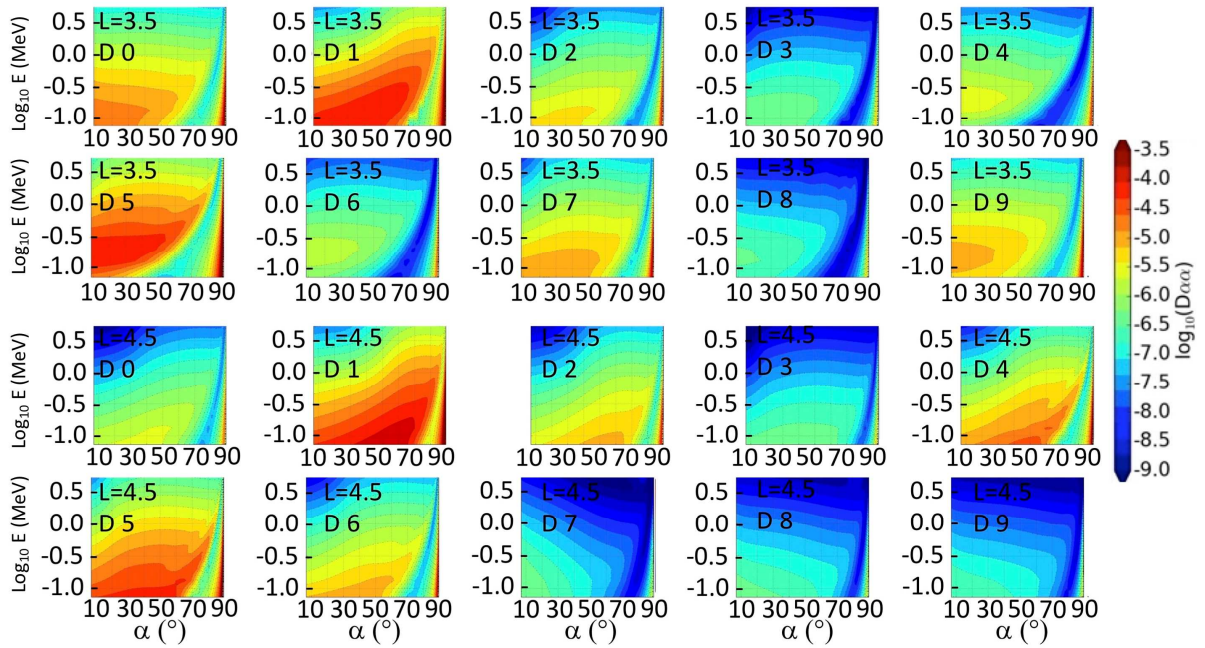


914

915 Figure 5: (left) The ratio of the plasma frequency to the equatorial gyrofrequency
 916 (f_{pe}/f_{ce0}) for the first 10 days of July 2014. Verification of the (middle) low frequency
 917 ($\omega_m/\omega_{ce0} < 1$) and (right) dense plasma ($\omega_m\omega_{ce0}/\omega_{pe}^2 \ll 1$) limits taken in the
 918 computation of the diffusion coefficients. To be valid, the first limit (Figure 4, middle)
 919 has to be lower than ~ 0.1 and the second (Figure 4, right) lower than ~ 0.01 . This
 920 corresponds to black and blue regions (i.e. almost everywhere), thus giving confidence
 921 in the results for most of the domain. Small exceptions are noticeable on the July 3 and
 922 10 above $L=5.2$, in concordance with the main substorm (July 3) and the high-speed
 923 solar wind-stream (July 10). During the various substorms on July 3, 4, 7 and the HSS,
 924 f_{pe}/f_{ce0} drops by a factor ~ 4 , from 20-25 down to ~ 6 .

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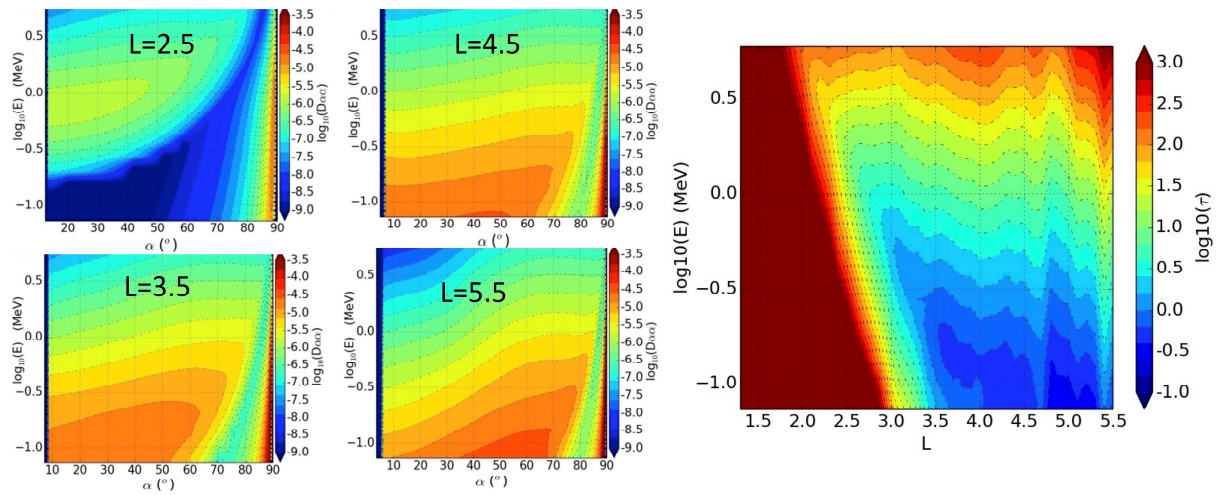
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928 Figure 6: Diffusion coefficients in the (Energy, pitch angle) plane, shown for the first 8
929 hour interval of each day of the 10-day period at (top two rows) L=3.5 and (bottom two
930 rows) L=4.5. This shows the daily variability of the diffusion coefficients at fixed L-shell.

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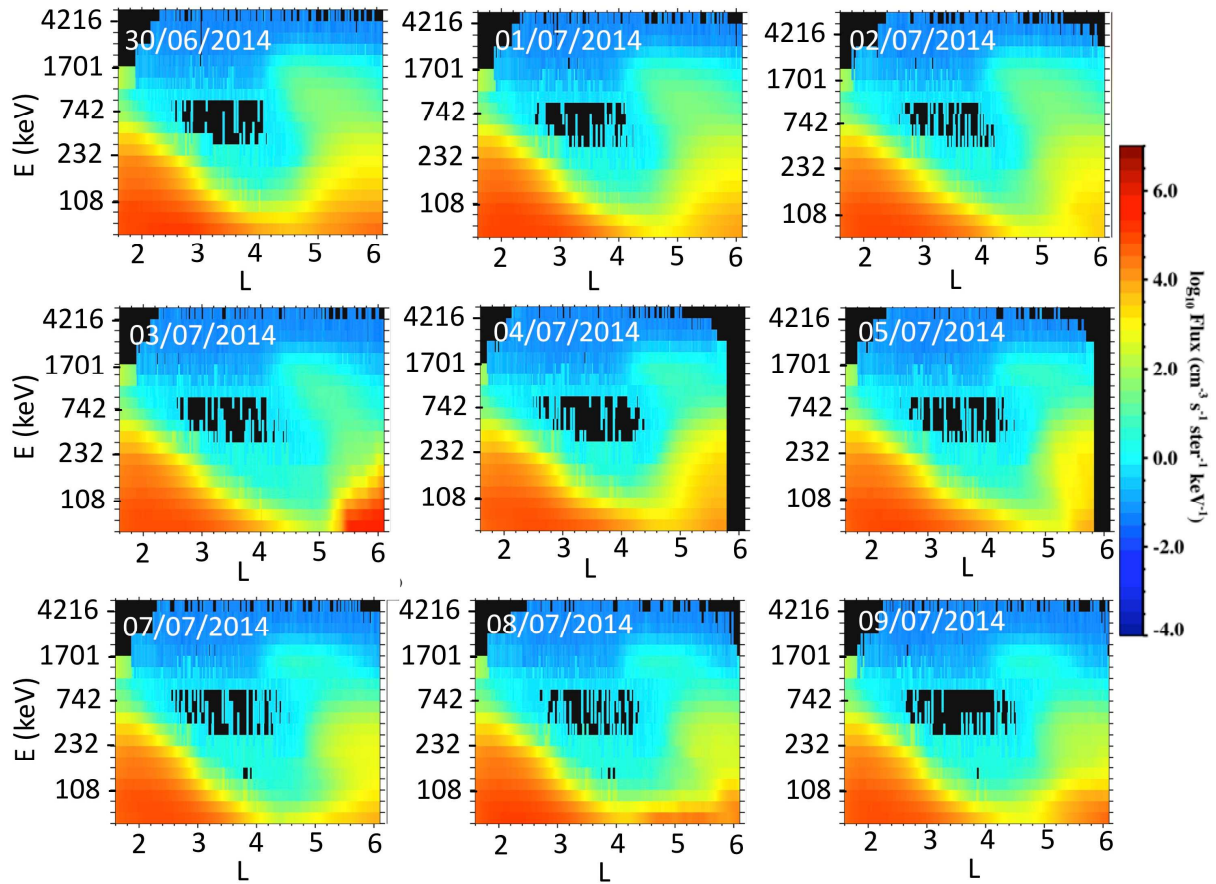


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935 Figure 7: (left) Averaged diffusion coefficients $\log_{10}(D_{\alpha\alpha})$ (\log_{10} of s^{-1}) for the period of
 936 interest, plotted at fixed $L = 2.5, 3.5, 4.5, 5.5$ in the (E, α) plane. At fixed L shell, maximal
 937 cyclotron pitch angle diffusion occurs at higher energy as pitch angle increases (for $\alpha \leq$
 938 70°). (right) Averaged electron lifetime in the (L, E) plane for the period of interest,
 939 showing 2 regions of high scattering above and below $L \sim 4.7$ for electrons of less than
 940 ~ 500 keV, which are discussed in section 3.3.

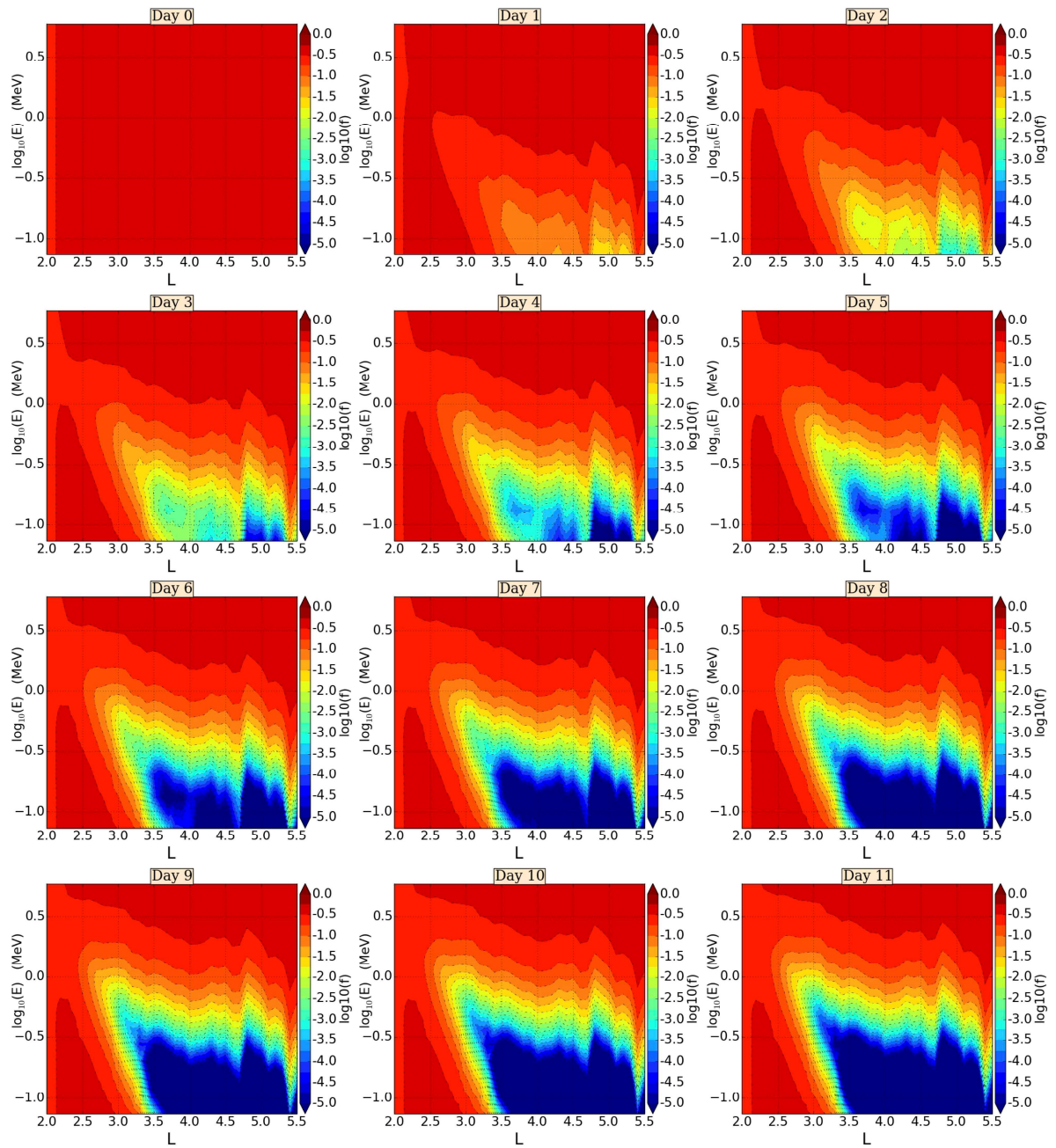
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944 Figure 8: Snapshots of MagEIS measurements in the (L shell, Energy) plane of the
 945 electron flux for each outbound path (~8h), unless unavailable, from June 30 to July 9
 946 2014 (omitting July 6). We observe the slot region forming between the belts during 10
 947 days and gradual removal of the outer belts. Substorm activity is also visible, e.g., on the
 948 July 3, with influx of electrons below ~200 keV.

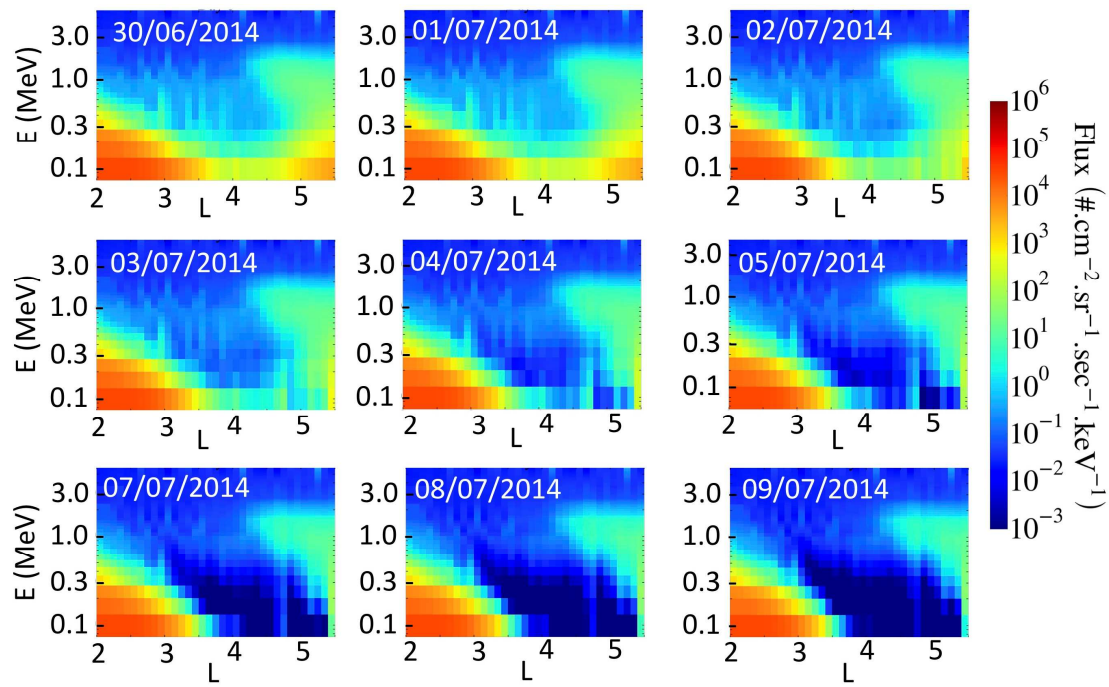


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951 Figure 9: Evolution of the simulated omnidirectional flux during 12 days, plotted at the
 952 beginning of each day. The first panel (Day 0) indicates the initial condition that is
 953 homogeneous in energy.

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957 Figure 10: Evolution of the simulated omnidirectional flux from 06/30/2014 to
 958 07/10/2014, plotted at the beginning of each day (omitting the 06/10/2014). The first
 959 panel (Day 0) indicates the initial condition given by the MagEIS spin-averaged flux on
 960 30/06/2014 6:54-11:31 (first panel of Figure 7).

961